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OPTIMISATION OF FACTORS INFLUENCING THE EFFICIENCY

OF FINISH MACHINING OPERATIONS

- by -

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C O N T E N T S

1. SUMMARY

Optimum machining conditions were determined for various materials, steels, cast irons, brasseses, bronzes and an aluminium alloy. Surface finish readings were taken with the Sigmatex and the Surtronic and values of 10 micro-in and below were obtained at 0.001 ipr feed both under dry and wet conditions. The tests were extended to higher feeds, the maximum being 0.004 ipr; at this feed, the surface finish fell, in most cases, below 20 micro-in.

It was found necessary to use high cutting speeds of the order of 800 to 1000 fpm in most cases. The most efficient tool used was a Titanium Carbide which successfully machined the whole range of test materials.

The factors which were found to discourage the production of a good surface finish, given the right feed and speed, were scratching of the chip on the finished surface, bad blending of the nose radius with the two cutting edges, wrong order of grinding the flank clearance faces and the top rake face. The factors which encouraged a good surface finish were the choice of the right tool material, a suitable facet or chip deflector.

2.00 INTRODUCTION

Work pieces made from a wide range of materials and of exceptionally high accuracy could be produced at a low cost if one further important requirement were satisfied. This is that the very complex interaction between machine and work material should be of a satisfactory and consistent nature over long periods of time and the wear on the cutting tool should also be reduced to the minimum. This is possible when machining free cutting non-ferrous materials. To satisfy this condition when machining a wide range of materials whose machining properties are neither good nor fully understood is more difficult.

This research project, therefore, is an investigation into the optimisation of the factors which are known to influence the efficiency of finish machining operations. The main lines of investigation are:

(a) A survey of the tool materials in current use for finish machining in industry.

(b) A survey of the quality of surface finish of tool and workpiece usually demanded in industry for the most common finished products.

(c) An investigation into the optimum tool geometry.

(d) An investigation into the optimum cutting speeds.

(e) An investigation into the optimum feeds.

(f) An investigation into the optimum chip thickness.

(g) Assuming optimum conditions for the factors above, an investigation into the effect of tool, workpiece and machine rigidity on the surface finish produced.

(h) An assessment of the effect of the use of lubricants under the above optimum conditions.

(i) An assessment of tool life under the above optimum conditions.

Finish machining operations are characterised by relatively small depths of cut and low feed rates, resulting in machined surfaces of high quality. Depths of cut for finish machining are normally less than 0.06 in., (1), and the feed rate less than 0.006 ipr.

The type of machining operation considered here is the turning operation using a conventional tool with a nose radius.

The nomenclature used here for tool geometry is shown in Fig. A1, Appendix 1.

2.01 Measurement of surface finish

Surface finish is usually measured by a diamond stylus that traverses the surface, the vertical motion of the stylus being magnified and recorded. The roughness is expressed in the following two possible ways:

1. Maximum peak to valley value.

2. The Centre Line Average (C.L.A.) or Arithmetic Average value.

The latter system is used in Britain and U.S.A. while the former applies to the Continent.

There are two distinct types of finish encountered in turning:

(a) The finish produced by the primary cutting edge.

(b) The finish produced by the secondary cutting edge.

These two cutting edges are shown in Fig. 1. In a conventional turning operation the finish left on the bar is produced by the secondary edge which is separated from the primary edge by a nose radius. This use of the secondary edge to generate the newly machined surface causes several complications.

1. Ridges corresponding to the tool at its nose and having a pitch equal to the feed rate are left behind on the finished surface.

2. Because the undeformed chip thickness reduces gradually to zero at the secondary edge, there is uncertainty as to the geometry of the cut at the trailing edge since for a given edge sharpness there is a minimum undeformed thickness that can be removed.

3. Concentration of wear at both free surfaces of the cut; the groove thus formed on the end cutting edge of the tool acts as a forming tool and leaves behind a severely cold worked ridge on the surface that not only contributes to the roughness but also produces additional grooves on the tool as the work surface is recut subsequently.

4. The material at the trailing edge of the tool is subjected to very high normal stress and flows to the side to relieve this stress thus producing a furrow that contributes to the roughness, especially in the case of a soft, ductile material.

In addition to the above, built up edge roughness, roughness due to imperfect cutting edges and roughness due to tool vibration will also be present.

The component of surface roughness due to tool nose geometry may be calculated, (1). When the nose radius is large and the feed small, the surface will be generated by the nose radius alone. From Fig. 2 it is obvious that the peak to valley height, h, may be obtained from:-

$$h = OT - OU$$
$$= r - \sqrt{r^2 - \frac{t^2}{4}}$$
$$= \frac{t^2}{8r} \qquad (1)$$

This equation holds so long as $\frac{t}{2}$ is less than EH.

2.02 Minimum Undeformed Chip Thickness

It was suggested, (2), that there was a minimum undeformed chip thickness below which a chip will not be formed and only rubbing will occur. This will depend on the sharpness of the cutting edge, the cutting speed and the stiffness of the system. Measurements indicated that for a cutting edge sharpness radius of 0.0005 in. and a cutting speed of 650 fpm, the smallest cut that can be taken was about 0.00016 in.; the work material was AISI 1045 steel.

2.03 'Squeezing' or Side Flow

The metal left behind on the secondary cutting edge is subjected to severe pressure which causes the metal to flow to the side as shown in Fig. 3. The profile left behind in the absence of side flow or 'squeesing', (3), is shown in Fig. 3(a) while Fig. 3(b) shows the profile with 'squeezing'. The peak-to-valley height is seen to be greater in the presence of side flow.

The influence of side flow on surface finish has been studied, (4), and showed that its component of roughness is zero for a brittle material such as free cutting brass but may contribute up to 240 micro-in, peak-to-valley height, when an alloy steel is machined. It was suggested that the side flow contribution to roughness decreases as cutting speed increases.

2.04 Cutting Temperature

It is not only important in finish machining that the cutting temperature should be sufficiently high in order to eliminate the built up edge, the layer of material adjacent to the tool face must be thermally softened to provide low friction and a high shear angle. The cutting temperature will depend on the hardness and ductility of the work material, the cutting speed, feed and depth of cut. Finishing cuts are usually of small depths and small feeds hence such a material as normalised AISI 1045 steel must be machined for optimum conditions at 1200 fpm and 0.0016 ipr. But such speeds are difficult to obtain with bars are of about 1" dia. Lower speeds are therefore obligatory, hence adjustment of other variables as feed, workpiece hardness or tool geometry in order to compensate for loss of temperature due to decrease in speed becomes necessary.

The chip equivalent was introduced, (5), as a means for determining the influence of tool geometry on the relative cutting temperature. The chip equivalent:

$$CE = \frac{L}{bt} \tag{2}$$

Where L is the active length of the cutting edge.

b is the depth of cut

t is the feed.

It was shown that when a given material is cut the temperature will vary inversely with the chip equivalent. Thus the cutting temperature will be increased with a decrease in chip equivalent. Therefore in the majority of practical cases where it is difficult to cut at a sufficiently high speed, it is advisable to use a short chip equivalent. This is achieved by the use of a zero approach angle and a moderate nose even though the latter conflicts with the fact that the theoretical finish improves with increase in nose radius.

Other variables that influence the cutting temperature are side and back rake angles because they influence the effective rake angle in the plane of chip flow. The cutting temperature will increase when the effective rake is decreased by a decrease of side rake or as the back rake approaches zero. It was suggested, therefore, that for higher cutting temperatures, a side rake of zero degrees will give better results than the more common rake of +10° normally used for medium cuts. A back rake of zero degrees was also suggested as an optimum for finish machining steel.

The hardness of the workpiece plays an important role in finish machining. For a work material that is too soft, side flow will be too great and it will take too high a speed to get rid of the built up edge and produce a thermally softened layer on the tool face.

2.05 Other Factors

Ductility is also an important factor. Free machining additives such as lead and sulphur decrease chip ductility and thereby greatly improve surface finish by providing a smaller built up edge and smaller tendency to side flow.

The sharpness of the cutting edge is also known to have some influence on the finished surface. Carbide tools lapped with very fine grit diamond wheels may give 20% better finish than those ground in an ordinary manner. While there is no initial difference in the finish machining performance between carbide and ceramic tools, it is found that worn carbide tools give better finish than worn ceramic tools because the same initial radius surface will be generated by the nose radius alone. From Fig. 2 it is obvious that the peak to valley height, h, may be obtained from:-

$$h = OT - OU$$
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ends up as a much larger radius in a worn ceramic tool especially in the case of tools of coarser grain size.

2.06 Cutting Agents

It was shown, (6), that a chemically active cutting agent can reduce roughness by a factor of 4 or more at moderate speeds. The effectiveness of a fluid, however, falls off rapidly at proper cutting speeds and in addition may cause accelerated tool wear due to the formation of a series of cracks running perpendicular to the cutting edge; these are called 'comb' cracks. For this reason it is advised that cutting at normal speeds should be done dry.

2.07 Survey of Tool Materials in Current Use

Visits were made to various firms including small, general engineering firms, sub-contractors and some big firms in the motor car industry. Quite a few of the firms were members of the Institute of Fasteners and Turned Parts.

One fact that emerged was the number of firms that still only use High Speed Steel and Stellite tools and have not yet progressed to carbides. The reasons advanced were as follows:

1. That they had always found H.S.S. and Stellite tools sufficient for their purposes.

2. That carbides were expensive and operators on the shop floor could not be trusted to treat them with proper respect or use the necessary care in regrinding.

3. To justify the use of carbides, high speeds were often necessary and some of their machinery were not capable of these speeds.

2.08 Uniformity of the Properties of Steels

Almost the most common comment encountered during the visits was that the biggest problem facing the machinist was not to find out the optimum conditions for machining various materials but to discover materials with uniform or practicable machining properties. It was not out of the ordinary to set the same machining conditions for one bar only to find they were not as satisfactory as they had been for another bar of the same batch.

A report, (7), was written on this problem with particular attention to steels. It dealt in detail with the manufacture of steels, the complexity of the various processes involved being so great that rigid control of the proportions of the constituents to any high degree of accuracy is economically impossible.

In considering consistency in machining, the fault must not always be laid completely at the door of the suppliers of the bars. Lack of uniformity also exists in tool material and could be partly responsible for inconsistency in surface finish.

In an attempt to avoid variation due to work material and tool material properties it was decided to obtain enough work material and tools from the same sources and at the same time to ensure that they came off the same batch.

Lack of uniformity of material is a factor beyond the control of the operator. Factors within his control, however, are:

1. Tool rigidity; this involves two factors, the tightness with which the tool is clamped on to the tool post and the length of tool overhang.

2. Consistent tool preparation; with the same tool and the same grinding wheel, it is possible to obtain a variety of surface finishes on the same workpiece. These depend on the following factors:

(a) The state of the grinding surface of the wheel.

(b) The direction of grinding of the flank and top rake faces.

2.09 Feed Rates: During the initial part of the programme, one constant criticism from industry was that it could not afford to cut at the very low feed rate of 0.001 ipr as it was very time consuming; feeds of 0.003 and 0.004 ipr were more common for finish machining. This criticism would be valid if the cutting speeds employed here were as low as those employed in industry. Cutting speeds of 300 fpm were recommended at various firms for finish machining low carbon steels; the associated feeds were usually 0.003 or 0.004 ipr. The corresponding conditions recommended here would be 1100 fpm and 0.001 ipr. From the curves on Fig. 7 showing cutting time against feed rate for a 3″ dia. bar and 3″ gauge length, it can be seen that there is even a slight saving time at the higher cutting speed and lower feed combination. There is, of course, the problem that the higher speed would mean increased wear but it is believed that the right choice of tool material, sufficient care in grinding and a suitable lubricant would help to counterbalance the high cutting speed.

It can be seen from Fig. 7 that cutting speed begins to lose significance at the higher feeds and speeds. Thus cutting times for 1100 fpm and 1300 fpm are almost the same at 0.004 ipr while at 0.001 ipr the time for 1100 fpm is much less than for 1300 fpm.

3.00 EXPERIMENTAL PROCEDURE

3.01 Work Materials

The range of materials covered by the test was as follows:

Steel Bar (En Series): 1A, 3B, 8, 32A, 35, 37, 56A, 57, S99

Cast Iron Bar: BS1452, BS2789

Brass Bar: BS249, BS369

Bronze Bar: BS250B, DTD160

Aluminium Alloy Bar: L65

The bars were mostly 3" dia., this being a suitable size that would allow sufficiently high surface speeds to be achieved while not being too heavy for the lathes.

Considerable interest in the research programme was expressed by Guest, Keene and Nettlefold Ltd., who offered to supply us, free of charge, with whatever we required in the way of steels that they had in stock.

3.02 Tool Materials

The fact that reasonably high speeds were envisaged limited the tool materials to carbides and ceramics. The latter are very delicate, and require machines to be very rigid or are liable to shatter; furthermore, as explained in Section 2 05, they are not quite as good as carbides once wear sets in.

Table 1 shows a list of the carbides used during the tests. They were supplied by Production Tool Alloy (Perpro) Ltd. mostly in the form of brazed tools though quite a few throw away tips were obtained later, particularly of the MX grade, and brazed on here.

TABLE 1

Percentage Composition of Carbides

Grade P.T.A.	I.S.O.	WC	TiC	TaC	Co	Mo	Ni	Density gm/cc	V.P.N.
AU	K10	94.25			5.75			15.0	1700
AW	K10	85	7.75	1.5	5.75			12.9	1800
MX	M05	11.5	64			11.5	11	6.1	1800
PD	P30	84.7			8.5			13.3	1500
PF	P25	79.5	5	7	8.5			13.15	1425
PZ	P10	60.5	17.5	12	10			10.7	1600

The following is a description of the application of the carbides:

3.02(a) AU (ISO K10): This is suitable for finish machining where high abrasion resistance is required. When brazing and grinding this grade, extreme care should be taken to limit thermal stresses. Recommended for machining cast iron and non-ferrous alloys.

3.02(b) AW (ISO K10): Lighter and harder than the AU grade, therefore more hard wearing. Also recommended for machining cast iron.

3.02(c) MX (ISO M05): Because it consists mostly of TiC, this grade is very light and hard. Suitable for high speed finish machining of a wide range of materials. Extreme care should be exercised to limit thermal stresses when brazing and grinding.

3.02(d) PD (ISO P30): Suitable for machining high tensile steels above 60 t.s.i. and also aluminium alloys that tend to build up on the cutting edge.

3.02(e) PF (ISO P25): Recommended for machining stainless steels, particularly castings, because of its high TaC content.

3.02(f) PZ (ISO P10): The high TiC and TaC content gives this grade extreme resistance to flank and crater wear on high speed finish machining of steel; intended for use mainly in general finishing.

3.02(g) Diamond Tools: Two types of diamond tools were obtained from van Moppes of Basingstoke, B5B/U1.2 and 7F/U1.2. The former is a Vee tool, prepared to B.S. specification 1120 under the symbol B5B while the latter is designed with a few facets in the cutting edge.

Working conditions recommended for diamond tools are that only machines without noticeable vibration should be used, feeds should be of the order of 0.0005 to 0.0015 ipr, depths of cut not to exceed 0.005 in. and the workpiece must be rotating before the cut commences.

3.03 Equipment

The equipment consisted of the following:

3.03(a) Colchester Chipmaster Centre Lathe: 5″ swing, 20″ between centres with infinitely variable speed control via a Kopp variator up to 3000 rpm.

3.03(b) Holbrook Magna Centre Lathe: 7″ swing, 30″ between centres, with a range of twelve fixed speeds from 30 to 3000 rpm. Since a lathe with variable speed control was thought necessary, it was decided to modify this machine through a hydraulic system into a variable speed lathe. Boulton-Paul Aircraft Co. were therefore asked to design and supply the hydraulic system. Considerable trouble was encountered in obtaining the design and more still before the parts all arrived. The assembly of the lathe and hydraulic system is shown in Plate 1. The difficulty encountered in finding a lathe suitable was that no variable speed lathe of the size required was available at short notice at the time.

3.03(c) Tool and Cutter Grinder: Jones and Shipman Model 311; this was one of the first three machines of this model in production. Its main advantage is its universal head capable of rotating through 360° in two orthogonal planes. This makes it easy to prepare tools of complicated geometry.

3.03(d) Baker-Pera Nose Radius Blending Attachment

This equipment enables the operator to grind the approach and trailing faces of a tool and blend the two faces together in a smooth radius; the exact size of the nose radius that joins these two faces, otherwise known as the primary cutting edge and the secondary cutting edge, together can also be read off a graduated scale. This attachment is shown in operation on Plate 2 which also shows the Tool and Cutter grinder, universal vice and dust extractor unit.

The importance of blending the nose radius smoothly is shown in Table 2 which compares a tool ground properly with one where no special care has been taken to ensure that the nose radius blends in properly with the primary and secondary cutting edges.

TABLE 2

Material En 1A Tool: PD Cutting Speed: 600 fpm

Lubricant	No deflector	
Feed	Surface Finish : micro-in.	
ipr	Nose radius not blended	Nose radius blended
0.001	30	24.5
0.002	32.5	22.5
0.003	37.5	27.5
0.004	38	32.5

The table shows clearly that the nose radius must blend smoothly with the cutting edges otherwise a line is generated where the radius meets either edge. This line is detrimental to the production of a good surface finish and also sets up a region of stress concentration that accelerates tool wear.

3.03(e) Surtronic Surface Texture Meter: This is shown in position on the Colchester lathe on Plate 3 and is capable of giving readings in micro-in. and microns C.L.A. with a range of 0-1000 micro-in. It makes use of a sharply pointed stylus (0.0005 in radius) to trace the profile of the irregularities of a machined surface, a rounded skid providing the datum. The drive unit traverses the pick-up across the surface and the resulting electrical signals from the pick-up are amplified and used to drive the Average Meter. The instrument is very versatile; the pick-up will give a measure of the vibration intensity on any part of a machine to measure the surface texture of a turned bar in position on a lathe. The stroke of the stylus is variable. The instrument is marketed by Rank-Taylor-Hobson.

3.03(f) Sigmatex: This is another surface texture measuring instrument whose measuring head can be used either clamped on its stand or rested on the surface to be measured. The stylus stroke is about 3/16" and the range of the instrument is 0-200 micro-in C.L.A. This instrument was, unfortunately, subject to frequent troubles and it may be fair criticism that it will not stand up to daily use over an extended period. The model has now been discontinued by Sigma Instruments, Letchworth.

A test comparing the Surtronic, Signatex and the Talysurf showed the Surtronic to be the most accurate.

3.03(g) Grinding Wheels: This subject is dealt with under a separate item from the Tool and Cutter Grinder because the type of grinding wheel used was found to have great influence on the surface finish produced. Three types of wheel were used, the first being a ceramic bonded diamond impregnated wheel of specification SD/280/P/100/V$^1/_8$" where:

SD : synthetic diamond

280 : grit size

P : bond hardness

100 : diamond concentration

V : vitrified ceramic bond

$^1/_8$: depth of diamond impregnation.

This wheel turned out to be unsuitable for grinding without a fluid which could not be used in the presence of the grinding attachment.

Another wheel which could be used dry with the dust extractor unit was obtained. The specification for this was SD/240/N/50/D$^1/_{16}$"M_1 where the letters and figures compare with the previous wheel except:

240 : grit size, slightly coarser than first wheel

N : bond hardness, two grades soften than P

50 : concentration half as dense

D : indicates that the wheel hub is y aluminium alloy.

$^1/_{16}$": depth of diamond impregnation

M_1 : indicates that the type of bond is resinoid

This wheel had a much softer cutting action than the ceramic bonded wheel.

The third wheel was similar to the second except that the grit size at 400 was much finer and therefore produced a better finish on the tool resulting in a much improved surface finish.

3.04 Cutting Tests: Preliminary tests were carried out to standardise some of the factors involved in producing a consistent surface finish.

3.04(a) Tool Overhang: With the tool shank section ($^3/_4''$ deep x $\frac{1}{2}''$ wide) and light loads employed in finish machining, there is not much change in surface finish for an overhang below $1\frac{1}{2}''$, this is shown in Fig. 4. When the load is varied, Fig. 5 shows that the overhang must be kept to the minimum; the overhang was kept at $1''$ throughout the tests.

3.04(b) Type of Diamond Wheel: The original wheel recommended for use with the radius blending attachment was ceramic bonded. This gave a poor finish and resulted in a poor work material surface finish. The wheel was later replaced by a resinoid bonded wheel which proved more satisfactory as the following figures indicate.

Wheel bond	Grit Size	Tool Finish	Surface Finish
Ceramic	280	18 micro-in	47.5 micro-in.
Resinoid	240	4.5 micro-in.	26.8 micro-in.

With the same tool and the same grinding wheel, it is possible to obtain a variety of surface finishes. These depend largely on the following factors:

(i) The state of the grinding surface of the wheel, whether or not it is clogged up with brazing or shank material. Care was always taken to relieve the cutting edges of shank material before being ground with the diamond wheel. The brazing material sometimes tends to clog up the wheel especially where the latter is of very fine grit.

(ii) The direction of grinding of the clearance and top rake faces. There are three possible grinding directions as shown by the arrows, 1, 2 and 3 on Plate 4. There are also three possible ways of combining these three directions, (1 or 2, 3); (3, 1); (3, 2). This is also the preferred order, the first figure indicating the first direction of grinding.

Table 3 shows the resulting surface finish using these three combinations.

TABLE 3

Cutting Speed: 1000 fpm. Tool: MX Specimen: Brass BS 369

Order of Grinding	Diamond Grit	Surface Finish : micro-in			
		Feed ipr			
		0.001	0.002	0.003	0.004
(1, 3)	240	15	16	15	18.5
	400	12	14	13.5	14
(3, 1)	240	12	13.5	15	18.5
	400	11	13.5	14	15.5
(3, 2)	240	8.5	12.5	14	17.5
	400	8	12	13	15

The specimen used was brass BS 369 in preference to steel since the wear involved is much less than for steel and it was therefore possible to use the same tool for the four feeds without regrinding and possibly altering the profile of the tool edge.

It can be seen that (3, 2) gave the best readings. This is because the wheel tends to leave a serrated edge where it leaves the tool surface. (1 or 2, 3) thus leaves a burr along the upper edge of the flank face which discourages the production of good quality surface finishes. (3, 1) leaves a serrated edge at the nose radius along the secondary cutting edge; the profile of these serrations is traced out on the finished surface. (3, 2) leaves serrations at the primary cutting edge. This is not so bad since the finish left by this part of the cutting edge is cut away during the next revolution of the workpiece. Therefore (3, 2) is the best order of grinding.

The grit size of the diamond wheel also affects the finish surface. Incoporated in this part of the test was an investigation of the effect of grit size on surface finish. The two wheels used were 240 and 400 grits. It can be seen from Table 3 that the 400 grit wheel gave the better finish at each feed and for each direction. However the table also indicates that using the finer grit wheel is not enough to guarantee a better finish than the coarser grit; the direction of grinding is also important. Hence, from the table, the preferred order would be $(3, 2)_{400}$, $(3 - 2)_{240}$, $(3 - 1)_{400}$, $(1 \text{ or } 3, 1)_{400}$, $(3 - 1)_{240}$, $(2 \text{ or } 3, 1)_{240}$. All this can be seen at a glance in fig. 6.

Another factor beyond the control of the operator is the rigidity of the machine both from the point of view of a vibration-free motor over the range of speeds used and also the structural rigidity of the framework of the lathe. It was possible to check the former and its influence on the latter with the Surtronic, placing the stylus on the part to be checked and observing the behaviour of the meter needle. Alternately a cutting test could be performed and a trace of the resulting surface finish traced out on a talysurf. The frequency of the pattern gave some measure of the vibration behaviour of the machine at the speed of cut.

The results showed that the vibration on the Holbrook was much more severe than on the Colchester. To reduce the vibration in the latter case, the Kopp Variator was overhauled; the steel balls and cones were found to be coated and therefore replaced.

Another factor that contributed to an irregular surface finish on the Colchester was the fact that the distance moved by the saddle during each revolution of the specimen was not uniform. This was discovered from the photographs taken on the Stereoscan Electron Microscope at Cambridge Instruments, Cambridge. This is shown on Plate 5 where it can be seen that the feed marks are not equidistant. This effect was more evident at the lowest saddle speed of 0.001 ipr. The saddle was therefore dismantled and the slideway scraped. The resulting improvement can be seen in later plates.

3.04(c) Other Factors: Given optimum cutting conditions in feed, speed and tool geometry, there are some other factors listed below that affect the quality of the finished surface.

1. Scratching of the work hardened chip on the machined surface particularly at 0.001 ipr for ductile materials.

2. Tearing of the surface being machined at high feeds.

3. Squeezing effect when tool begins to wear.

For a good surface finish therefore it would be necessary to use such a tool geometry that the chip is prevented from scratching on the finished surface, cut at low enough feed to prevent tearing and also ensure that the tool material and the quality of the cutting point are such that early and severe wear are prevented.

Some materials work harden much more severely than others hence the chip produced by the more severely work hardening materials is so much harder than the parent material that the damage done in scratching the finished surface is much greater than in the case of low work hardening materials. For example, in the case of Manganese Bronze, the chip is so severely work hardened that it becomes brittle and sticks to the finished surface in small flakes, leaving a feathery surface.

At higher feeds the chip tends to flow away toward the tool shank and there is little need to use a tool with special geometry to control chip flow. At higher cutting speeds the tendency for the chip to flow away from the workpiece is increased even at 0.001 ipr but this solution to the problem is not always applicable as the need for optimum conditions often limits the cutting speed.

The two solutions devised for preventing the chip from scratching on the finished surface were as follows:

1. A tool with a flat or facet of optimum width.

This is shown on Plate 6.

2. A tool with a deflector as shown on Plate 4.

Plate 7(a) and (b) were taken when machining Manganese Bronze at 600 fpm. (b) shows a stage shortly after (a); the resulting damage to the finished surface is obvious. (c) and (d) show the result of providing a facet of 0.020 in width at the secondary edge parallel to the work axis. The resulting flow is away from the work surface. This solution is however applicable only to the softer non-ferrous alloys as it gives rise to chatter otherwise.

Plate 8 shows chip flow being controlled with a 'deflector', this name being given to the geometry used because it deflects the chip away from the workpiece. The advantage here is that the optimum geometry for the material can be maintained at the cutting point. The use of a chip-breaker was found to be impracticable since depths of cut were so small that the height of the chip-breaker would have been very difficult to grind.

4.00 RESULTS

4.01 Preliminary Results: The specimen, 3" dia. x 15" long, was divided, with parting tool grooves, into six sections. With the Sigmatex, measurements of surface finish were carried out over three lengths in each section, the worst reading being recorded. When the Surtronic was used, a long stylus stroke was used and the average reading recorded.

Clearance angles were standardised at 5°, the approach angle at 30° and trailing angle 5°.

The preliminary tests, carried out dry, were used to establish the effect of various factors listed below:

4.01(a) Effect of increase in speed: This is shown in Graph 8 for En 3B. It shows a continuous improvement in surface finish as speed increases. To simplify graph, only four depths of cut are shown though eight depths were taken to cover the range shown.

4.01(b) Effects of increase in depth of cut: This is shown in Graph 9 for six of the fifteen speeds used and shows clearly that the effect of increase in depth of cut is considerable at low speeds but insignificant at high speeds.

4.01(c) Influence of chip section: Graph 10 shows that for the same chip section the better finish is produced by whichever combination of feed and depth of cut that has the lower feed. Doubling the feed has much worse effect than doubling the depth of cut. At very high speeds, while the effect of changes in depth of cut is negligible, change in feed still has considerable effect. This is brought out clearly in Graph 11.

4.01(d) Combination of feeds and speeds: High speeds and high feeds are obviously a desirable combination as can be seen from Graph 12 where only 400 and 700 fpm are shown. At low feeds, increase in speed causes improvement in surface finish but at high feeds there is a break-even range which, for En 3B is 900 - 1100 fpm where any feed gives minimum roughness. This is shown in Graphs 13(a) and 13(b) for 0.003" and 0.010" depths of cut respectively.

4.01(e) Nose Radius: Graph 14 shows results of tests done with 0, 1/32" and 1/16" radius. It clearly indicates an optimum value of 1/32" for the rake angles used, i.e. 0°, 5° and 20°. This is further indicated by Graph 15 which shows tests done with the same three radii and shows a rapid breakdown of the zero radius tool at 20° rake angle for tests at 1100 fpm.

4.01(f) Back and side rake angles: Though the previous graph (Fig. 14) shows little difference between 0° and 5° rakes, it can be seen from Graph 16 that at 1500 fpm the optimum rake angle was 5°.

4.01(g) Approach angle: A value of 30° was used but was not found to be necessary for depths of cut below 0.015". At the low depths of the order of 0.005" used in most of the tests, the point where the approach land meets the nose radius is well outside the cutting region. This is however not the case with the trailing edge where the point is well within the cut. For the approach angle to bear any significance at 1/32" nose radius, it would have to be at least 60° for the point where the land meets the radius to come within the cut.

4.02 Final Results: Table 4 shows the results for all the materials; the tests were all carried out initially at 0.001 ipr and under dry conditions to facilitate changeover from one specimen to another and also to determine which materials could be machined dry or wet.

TABLE 4

All Tests Carried Out Dry

Feed = 0.001 in/rev; Depth of cut = 0.005 11; Approach Angle = 30°;
Clearance Angles = 5°

Work Material	Hardness V.P.N.	Tool Carbide P.T.A./ I.S.O.	Cutting Speed fpm	Rake Angle		Trailing Angle	Nose Radius in.	Flat (F) or Deflector (D)	Surface Finish micro-in C.L.A.
				Back	Side				
Brass BS 249	99.5	AU/K10	1100	5°	5°	5°	0.030	-	9
Brass BS 369	193	AU	1000	5°	5°	5°	0.030	-	10
		MX/M05							8
Mn-Bronze BS 250B	160	AW/K10	600	15°	5°	5°	0.030	F	8
Al-Bronze DTD 160	144	AU	1000	15°	15°	5°	0.060	D	9.5
		MX						D	12.5
Al-alloy L 65	152	AU	1000	15°	10°	5°	0.060	D	7.5
		MX						D	9.5
C.I.BS 1452	224	MX	650	10°	5°	5°	0.030	-	10.5
C.I.BS 2789	212	MX	700	10°	5°	2°	0.030	-	9.5
S.S.En 56 A	270	PF/P25	650	5°	5°	10°	0.030	D	8
		MX		15°	15°	5°		D	8
S.S.En57	317	PF	500	5°	5°	10°	0.030	D	8
		MX	800	15°	15°	5°		D	7.5
En 1A	186	PD/P30	600	5°	2°	5°	0.030	D	14
		MX	1000	-12°	-20°	5°	0.030	D	5.5
En 3B	190	PD	800	5°	5°	5°	0.030	D	11
		MX	1100	-12°	-20°	5°		D	7.5
En 8	205	MX	800	-12°	-20°	5°	0.030	D	10
En 32	176	MX	1000	-12°	-20°	5°	0.030	D	8
En 35		MX	1100	5°	10°	5°	0.030	D	8.5
En 37		MX	1000	-12°	-20°	5°	0.030	D	7.5
S99		MX	1000	-12°	-20°	5°	0.030	D	7

Table 5 gives the results for tests over a feed range of 0.001 to 0.004 ipr; a lubricant Metol 77, concentration 1 in 10, was used where appropriate. In cases where the lubricant was found to have no effect the wet test was not pursued.

TABLE 5

Lubricant: Metol 77 SURFACE FINISH (micro-in C.L.A.) AT VARIOUS FEEDS

Work Material	Cutting Speed ft per min.	Dry or Wet	Tool Material	Feed in per rev			
				0.001	0.002	0.003	0.004
Brass BS 249	1100	Dry	AU	9	13.5	17	18.5
			MX	8	10	12	16.5
			D-Facet	8	11	11.5	11.5
Brass BS 369	1000	Dry	AU	10	13.5	15	19
			MX	8	12.5	13	15
			D-Vee	10	15	16	30
			D-Facet	7	7.5	9	9
Mn-Bronze BS 250B	600	Wet	AW	8	9	10	15
	800	Wet	D-Facet	10	11	11.5	13
Al-Bronze DTD 160	800	Dry	AU	9.5	11	12	14.5
			MX	12.5	15	17.5	35
		Wet	MX	9	10.5	10	14
			D-Facet	8.5	10	11	13.5
Al-Alloy L 65	1000	Dry	AU	7.5	13.5	17	18
			MX	9.5	10.5	12.5	13
		Wet	MX	9	10	11	16
C.I.BS1452	650	Wet	MX	8.5	10.5	17	24.5
C.I.BS2789	700	Wet	AW	10	14.5	15	22.5
			MX	8.5	11	13.5	21.5
S.S. En56A	650	Wet	PF	9	12	16.5	25
			MX	7	9	10	12
S.S. En57	800	Wet	MX	8	7	8	7.5
En 1A	1000	Dry	MX	5.5	13.5	19	19
		Wet	MX	8.5	10	12	14.5
En 3B	1100	Dry	PZ	19.5	22	-	28*
		Wet	MX	5	9	11	14.5
En 8	800	Wet	MX	8	8	10.5	17
En 32	1000	Wet	MX	8	12.5	14.5	15.5
En 35	1100	Wet	MX	6.5	9.5	12.5	17.5
En 37	1100	Wet	MX	7.5	9	11	14
S 99	1100	Wet	MX	7	12	15	18

* Tool ground with 240 grit wheel; all other tools with 400 grit. (Tool geometry same as on Table 4)

From Table 4 it can be seen that the steel which tend to machine with built up edge formation, require high cutting speeds and negative rake angles to raise the temperature at the cutting zone to a sufficiently high temperature as to discourage built up edges, (1). The stainless steels were machined at much lower temperatures and positive rake angles.

From Table 5, the results for the diamond tools were correspondingly better than those of the carbides though not so much better as to justify the high cost of the diamond tools. The lathe used may not have been suitable for machining with diamond tools; it could be argued at the same that the machine was the same for both carbide and diamond.

The surface finish improves as the feed is reduced. This rate is not constant and follows no regular pattern; for some materials it is steep and for others almost zero. Fig. 17 shows a few examples of the surface finishes obtained under different conditions of feed and tool material for a brass, BS 369. Fig. 18 is correspondingly for Aluminium Bronze, DTD 160, showing results for dry and wet turning. Fig. 19 shows a cast iron BS 2789 for two carbides. Fig. 20 shows two stainless steels En 56A and 57 machined with two carbides. Fig. 21 shows En 3B, dry and wet, machined with two carbides and S99, an aircraft steel sent by B.A.C. which they required to be machined to below 26 micro-in, the best figure they could achieve. Figs. 17 to 21 were drawn from Table 5. The asterisk shows the reading for the corresponding dry 0.001 ipr test.

4.02(a) Stereoscan photographs: Some of the finished surfaces photographed under the stereoscan, showed many characteristics which would have been impossible to recognise otherwise. They showed:

(1) The effect of the irregular movement of the lathe saddle at low feeds (Plate 5).

(2) The squeeze marks at the feed lines (Plate 5).

(3) The tear on the machined surface that occurs at high feeds (Plate 9).

(4) The holes in the surface of cast iron (Plate 10).

The last two items explain why it is often possible to obtain both very good and very bad surface texture readings along the same bar. From Plates 9(b) and 10 it can be seen that it is possible to traverse the stylus along a line to avoid the tears or holes and another line that runs only along the smooth part of the surface. The stylus of the measuring instrument is shown in Plate 9(d), magnified 950 times. From Figs. 10(b) (X 1875) and (d) (X 950) it is obvious that the stylus is small enough to drop in and out of the holes as it traverses the surfaces.

Plate 9(a) shows the corresponding 0.001 ipr test to 9(b) at 0.004 ipr. The work material was En57. It can be seen that 9(a) is a clean surface and

and that a stylus would indicate a consistent texture over the surface. Plate 9(c) shows Manganese Bronze cut with a blended-facet diamond tool. The surface is very clean and uniform.

5.00 DISCUSSION

The project has shown that it is possible to obtain high quality surface finishes when the conditions are right. Perhaps the three most important factors affecting the quality of surface finish are:

(1) The care with which grinding is done to ensure that the nose radius is clean, particularly at the secondary cutting edge and that it blends smoothly with the two cutting edges.

(2) The chip deflector or, where appropriate, the facet.

(3) The correct tool material.

5.01 Blending of the Nose Radius: Table 2 shows the readings for a properly blended tool compared with a badly blended tool. Plates 11(a) and (b) show two stages in the grinding of a tool. 11(a) is similar to a badly blended tool; it also shows the method of setting the primary and secondary cutting edge tangential to the arc of a particular radius before grinding. 11(b) shows a properly ground tool with the nose radius smoothly blended into the cutting edges.

5.02 The Chip Deflector: The significance of the deflector is illustrated by Table 6 which compares the tests done for a tool with no deflector and one with a deflector. The deflector is $^1/_{16}''$ wide x $^1/_{16}''$ deep behind the cutting point parallel tc the length of the tool shank; Plate 4 top edge of

TABLE 6

Material: En 1A. Cutting Speed: 600 fpm. Tool: PD Lubricant: Metol 77

Feed ipr	Surface finish : micro-in.	
	No Deflector	With Deflector
0.001	24.5	15.5
0.002	22.5	18
0.003	27.5	23
0.004	32.5	26

the trailing face is now above the cutting point and because of the flank clearance angle, would be slightly nearer the workpiece and would interfere with the cut unless relieved. The photograph therefore shows the method of relieving near the arrowhead labelled 1.

The importance of preventing the chip from hitting the work surface is clear. The readings for the test with no deflector also illustrate why 0.002 ipr feed is often recommended, (1), for finish machining rather than the lower 0.001 ipr which should theoretically produce a better finish. At the lower feed the chip scratches on the work surface and produces a worse finish than 0.002 ipr where the chip tends to flow away and stay clear of the workpiece. In the presence of a deflector, column 3 in Table 6 shows that the lowest feed is the best. The facet or flat is merely another technique, similar to the deflector, of controlling chip flow.

To ensure that the facet ground on the tool for Manganese Bronze was square on to the workpiece each time the vice was disturbed, it was decided to modify the universal vice with a ball and spring arrangement in two planes, both for the zero position, so that the human error in lining the graduated scale with the datum mark was eliminated. The exploded view of the instrument is shown in Fig. 12.

5.03 The Correct Tool Material: Figs. 18 and 20 show that the carbide MX is a more successful tool than either the AU recommended for non-ferrous alloys or the PF recommended for stainless steels and even compares favourably with the blended-facet diamond tool. The carbide was a Research and Development grade, RD 128, at Perpro that had not, apparently, been used except as a negative rake throw-away tip.

Attempts to braze it as a tip on a shank and use it as a brazed tip have so far proved not very successful. The tips have usually cracked either before grinding, after grinding and before cutting or not long after the start of a cut. Some tips have lasted long enough to be used for tests over several hours but have usually cracked in the end.

This problem was made known to Perpro who have brazed some tips for the project but with the same results. Various methods of brazing have been tried, even Evostick and Araldite but without lasting success. There has not been enough time to go into any detail about the coefficient of expansion of the tool material, figures of the coefficient being available for all other grades but this one. There has been a suggestion that a more suitable shank material would solve the problem; this cannot be done till the facts are known about MX.

There is no doubt however that, in performance, the carbide far surpasses the other grades. Compared with the PZ grade, the finish on the surface of a tip ground with a 400 grit wheel was 2.5 micro-in as opposed to 4.5 micro-in for PZ. The finish MX leaves on work-surfaces is correspondingly smooth and very bright in appearance. Because it contains mostly TiC, it is very light and is extremely hard wearing and once the problem of brazing it is solved, should prove a successful finish machining tool on the market.

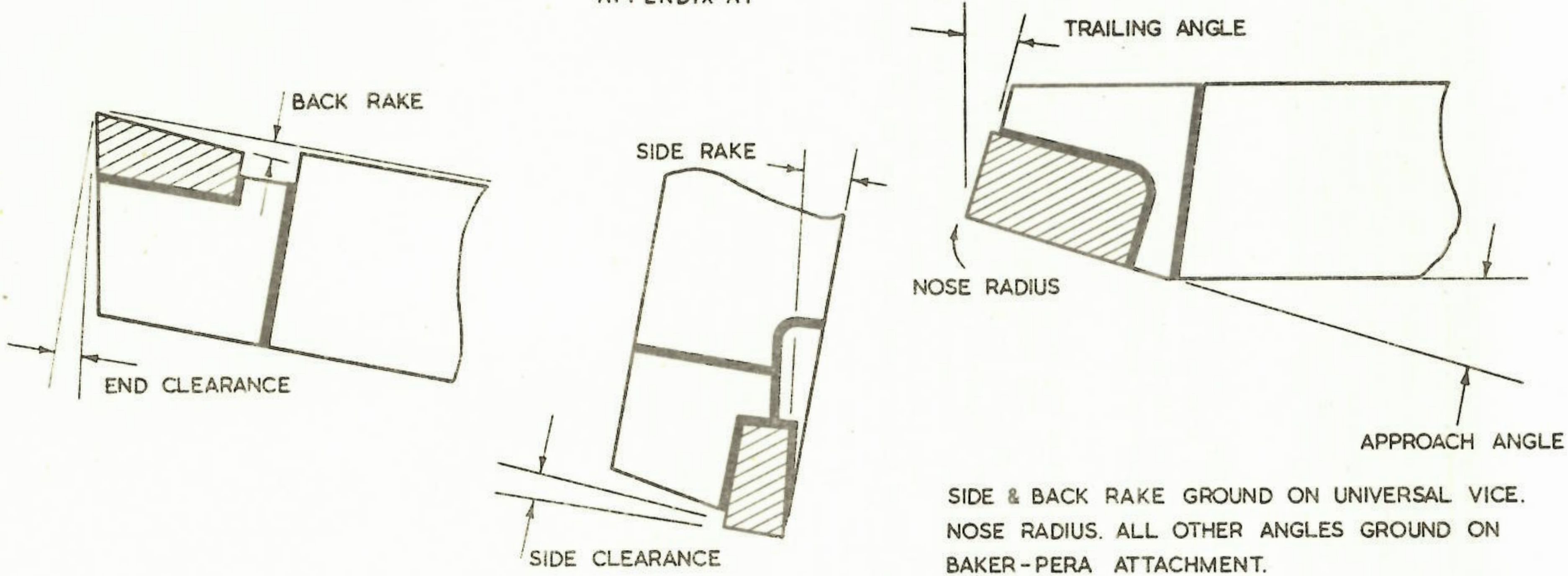
Part of this research programme was included in a 'Know How' television broadcast in December, 1968 and brought in many requests for more details. B.A.C. sent, via Perpro, a bar of S99. They wished to be able to machine it to a surface finish below 20 micro-in without having to grind it and thereby imposing stresses on the bar. The bar was machined here with the MX tool (-12° back rake, -20° side rake) and the results have been included in Tables 4 and 5; the 0.001 ipr reading was 7 micro-in.

The modification of the Holbrook Magna Lathe is not yet satisfactory completed since it is still subject to rather severe vibration.

The research programme has had some side products and two of these are reported in the Appendix. The first was a test on an additive to cutting lubricants, Chlorothene NU; this is manufacturered by Dow Chemicals Ltd. The second, drilling tests on a section of a bar of En 58M. This bar was sent by Dundee College of Technology on behalf of a firm which had difficulty drilling a sufficient number of holes before having to regrind their drills. The problem was solved by using a solid carbide straight fluted drill and a cutting oil treated with Chlorothene NU.

5.04 Tool Life: Detailed measurements of tool wear were not carried out but tool life was considered to the extent that the dry test at 0.001 ipr feed wes allowed to run for two sections of the bar, that is, about 5″ length of bar. If any noticeable wear had occurred then the surface finish at the end of the test was worse than at the start. In such a case, the cutting speed was usually reduced. The 0.001 ipr test on brass, B.S.249, for example, was allowed to run for 1 hour without change in surface finish. It must be accepted that some sacrifice will have to be made to obtain a surface finish about 10 micro-in in turning. This will take the form either of tool life or time taken in careful preparation of the tool.

APPENDIX A1



SIDE & BACK RAKE GROUND ON UNIVERSAL VICE.
NOSE RADIUS. ALL OTHER ANGLES GROUND ON
BAKER-PERA ATTACHMENT.

(FIG. A1) TOOL GEOMETRY NOMENCLATURE.

A2 Chlorothene NU as a cutting fluid

Plunge cutting tests were carried out on the end of a 16 gauge En 56C stainless steel 4" o/d tubing, the cutting tool being H.S.S. of 15° top rake and 10° flank clearance; the cutting speed was 160 ft per min and feed 0.0024 in per rev. These conditions were selected from preliminary tests to show measurable flank wear in reasonable time over the range of lubricants used.

The tests were done dry, with Garia 31 cutting oil, with G31 oil and 10% Chlorothene NU, with G31 and 25% Chlorothene NU and finally with the neat NU. The resulting flank wear, measured after every 2 minute cut to failure, is shown plotted against total cutting time on the graph in Fig. A2.

The graphs indicate that Chlorothene NU is most efficient as an additive for turning tests at 10% concentration. At 25% the mixture becomes rather thin and difficult to apply efficiently to the cutting area. The neat NU is so thin and evaporates so quickly that its use by itself is wasteful and inefficient; attempts to apply it neat were discontinued after the first test. This limitation does not necessarily apply to drilling or reaming blind holes where the cutting fluid stays in the hole all the time.

A3 Drilling tests on bar of En 58

Preliminary investigations to determine the classification of the bar were carried out. It was established to be 58 M, of hardness 360 V.P.N. Tests were then carried out with H.S.S. drills supplied so as to establish a basis of comparison for later tests. The conditions were selected to produce sufficient wear in reasonable time simply in order to reduce testing time. The depth of hole to be drilled was selected because of the flute length of the drills available.

The problem was to drill 90 two inch holes, $^{3}/_{16}''$ dia. before having to regrind the drill.

The conditions were:

Drilling speed	:	1120 rpm
Feed	:	6.25 in/min.
Drill dia.	:	5/32″
Depth of hole	:	$\frac{1}{2}''$
Drill materials	:	H.S.S. and Carbide
Cutting oil	:	Garia 31 with 10% Chlorothene NU.

Under these conditions the average life of the H.S.S. drills was 60 x $\frac{1}{2}''$ holes, the tests being terminated as noise due to friction became excessive. The corresponding wear at the cutting edges being 0.02″; the wear was measured every 10 holes.

Tests with solid carbide drills produced better results though the fast and slow spiral drills failed as a result of breakage rather than cutting edge wear. The test with the straight fluted drill was stopped after 360 x $\frac{1}{2}''$ holes though it was obvious the drill could have carried on for many more holes, the wear having been 0.0075″ since after the first 200 holes.

Carbide drills of 5/32″ and 3/16″ dia., are unfortunately not made with a flute length of 2″ and above. Therefore though 360 x $\frac{1}{2}''$ holes were drilled there is no justification for claiming this to be equivalent to 90 x 2″ holes. Tests were then carried out with H.S.S. drills to compare the effect of drilling 4 x $\frac{1}{2}''$ holes and 1 x 2″ hole. The same drill, reground before each test would however not drill 1 x 2″ hole after successfully drilling 4 x $\frac{1}{2}''$ holes.

Attempts were made in vain, especially at the Machine Tool Exhibition at Olympia to find a supplier for solid carbide drills of $2\frac{1}{2}''$ flute length. Apparently the diameter of 3/16″ was considered too small for such a flute length using so brittle a material as carbide. Similar vain attempts were made to obtain carbide tipped drills; these, it was said, only existed in the form of masonry drills.

The investigation therefore led to the following suggestions:

1. Straight-fluted drills are satisfactory but the diameter will have to be increased if a supplier is to be found or even if one were found for 3/16" solid carbide drills, if the drills are not to fail due to breakage.

2. H.S.S drills will have to be used, the operator being satisfied with a smaller number of holes before changing drills.

The author wishes to express his appreciation to the Science Research Council for the grant which supported this research programme, to G.K.N. Ltd. and their representative Mr. D.B. Clayton for the free supply of most of the steels used as work materials, to Perpro Hardmetal Ltd. (Production Tool Alloy) and their representative Mr. P. Newberry for their ready response to requests, frequently urgent, for more tools and, finally, to the various technical staff who have, in turn, been concerned with this project.

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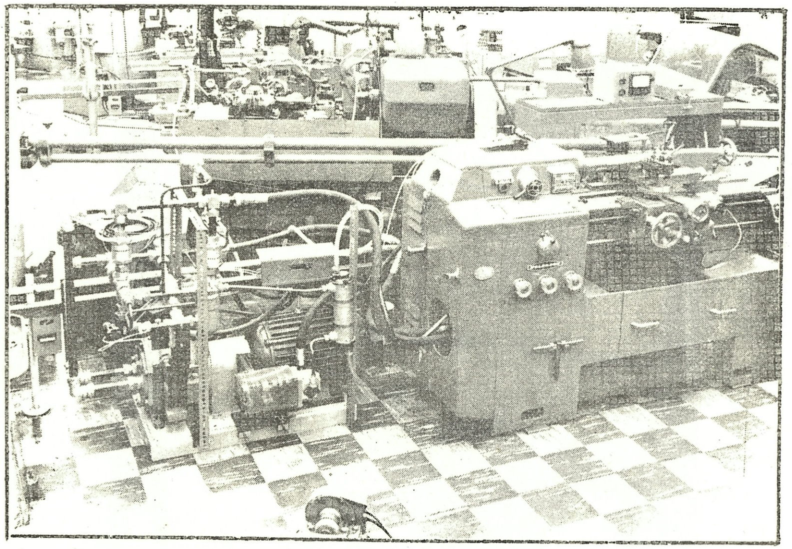


PLATE 1

HOLBROOK LATHE WITH HYDRAULIC DRIVE MODIFICATION

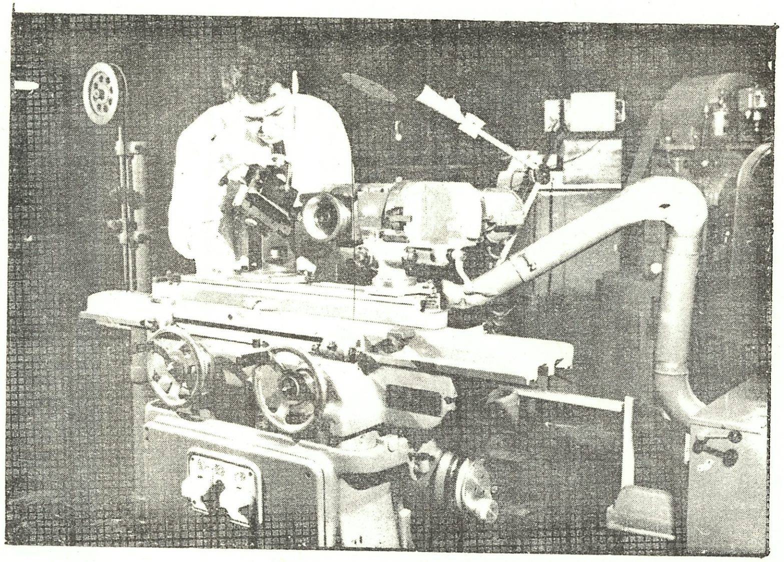


PLATE 2

TOOL & CUTTER GRINDER SHOWING BAKER-PERA NOSE RADIUS ATTACHMENT IN USE

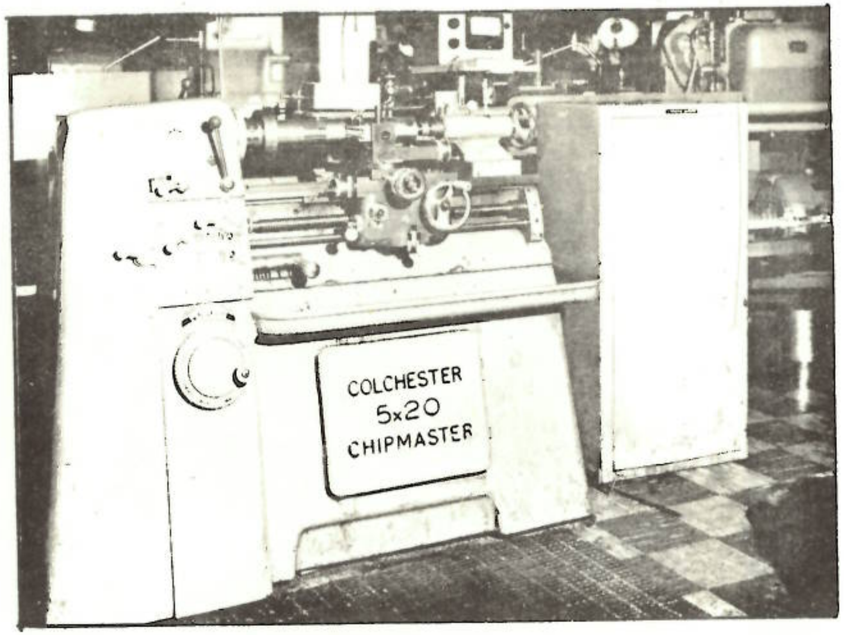


PLATE 3

SURTRONIC IN MEASURING POSITION ON LATHE

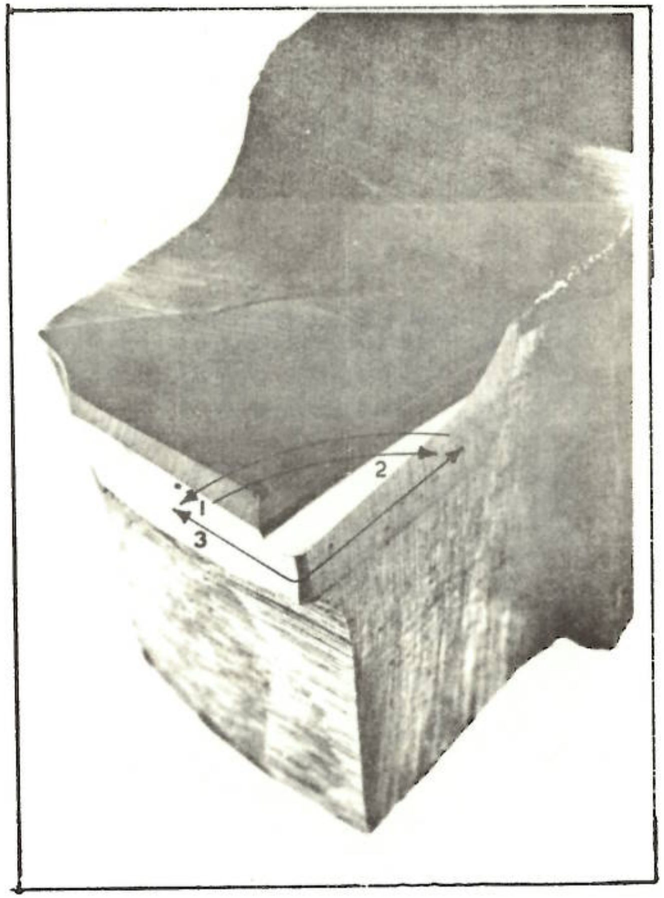


PLATE 4

TOOL WITH DEFECTOR, SHOWING ORDER OF GRINDING FACES

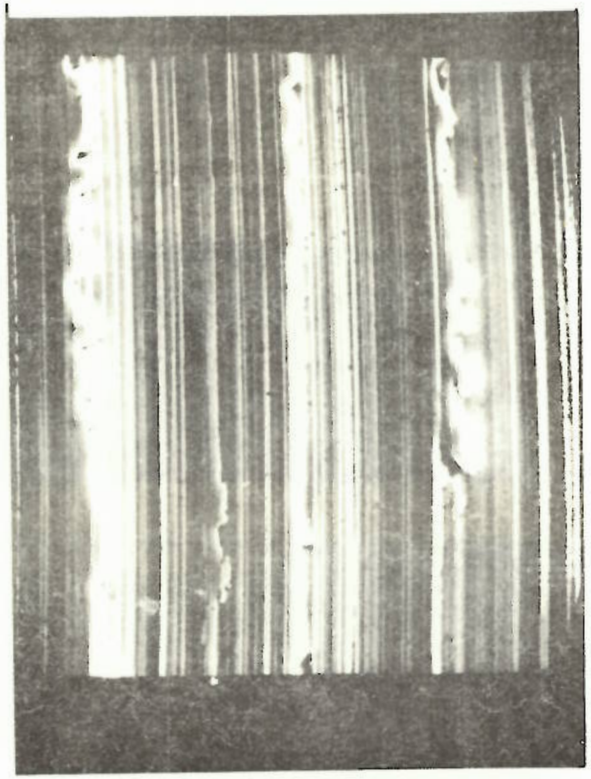


PLATE 5

"SQUEEZING" EFFECT ON SIDE FLOW

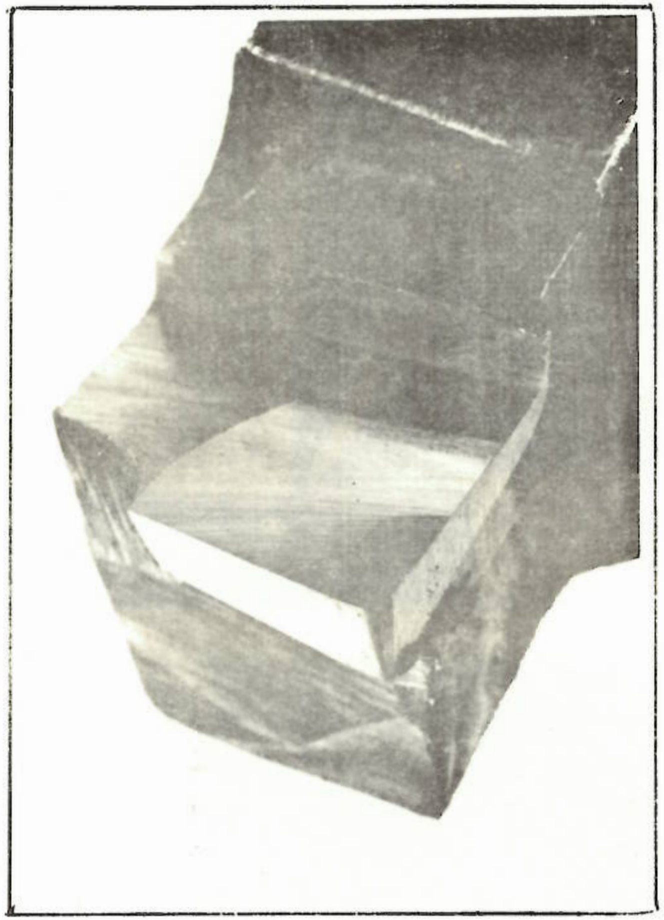


PLATE 6

TOOL WITH FACET, FOR MANGANESE BRONZE

CONTROL OF CHIP FLOW DIRECTION WITH A FACET

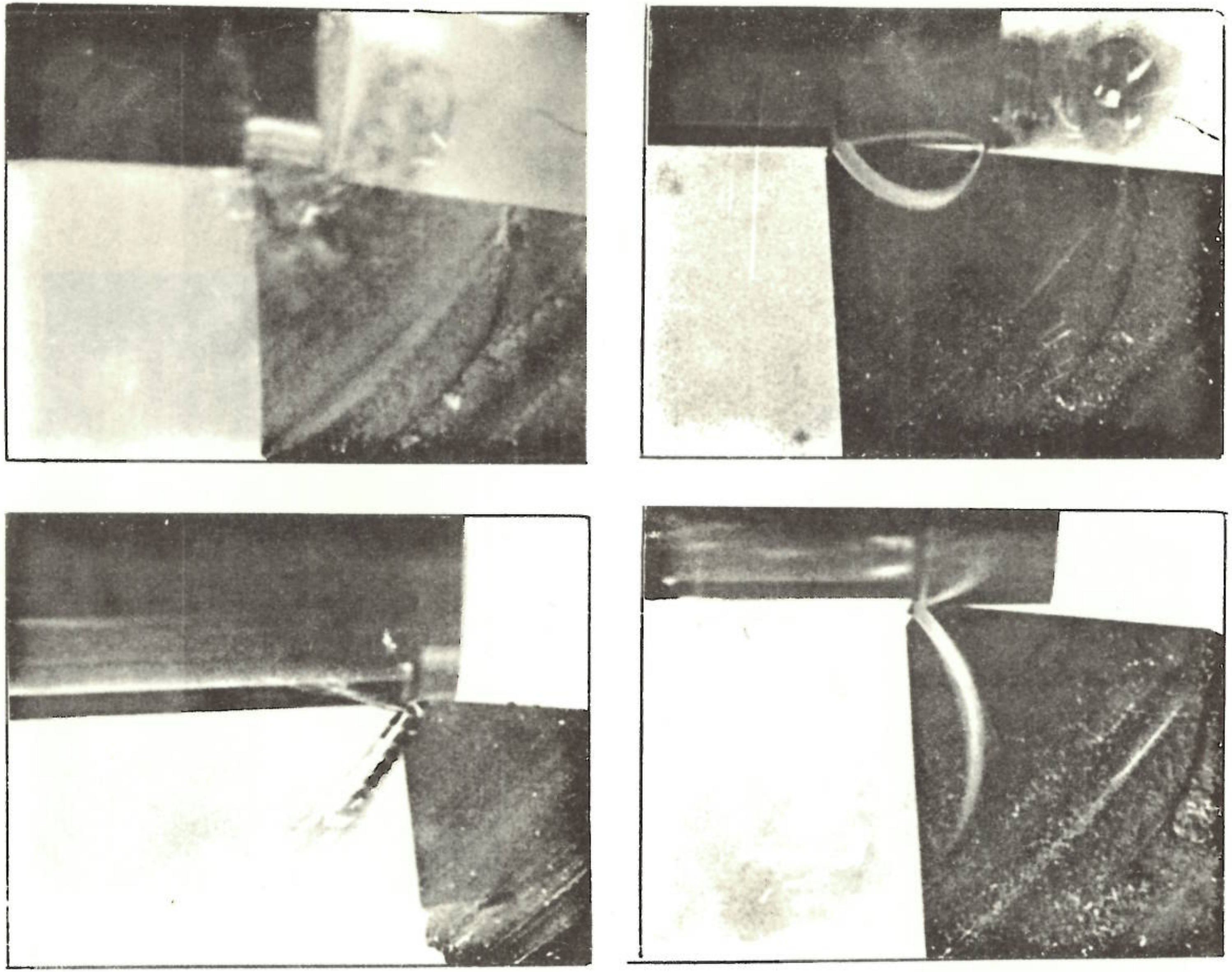
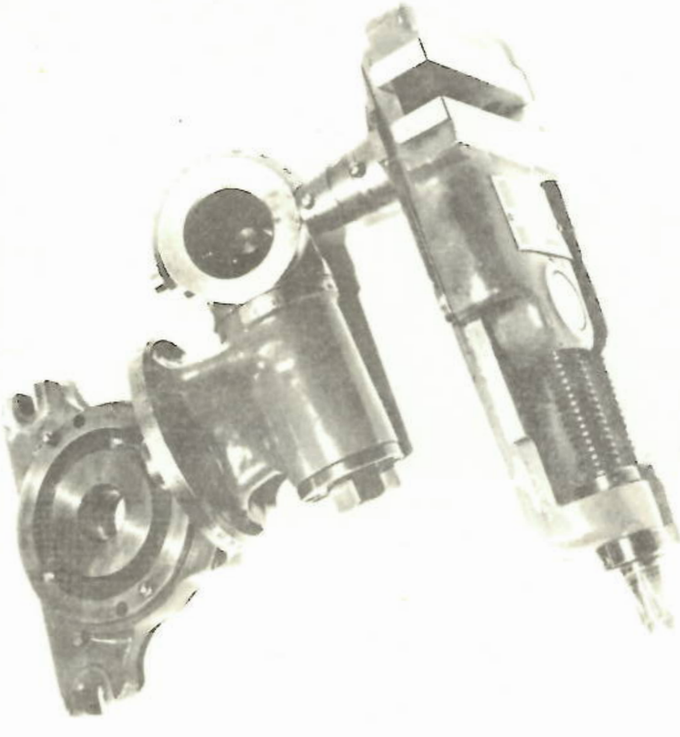


PLATE 7

CONTROL OF CHIP FLOW DIRECTION WITH A DEFLECTOR
c.f. PLATE 7

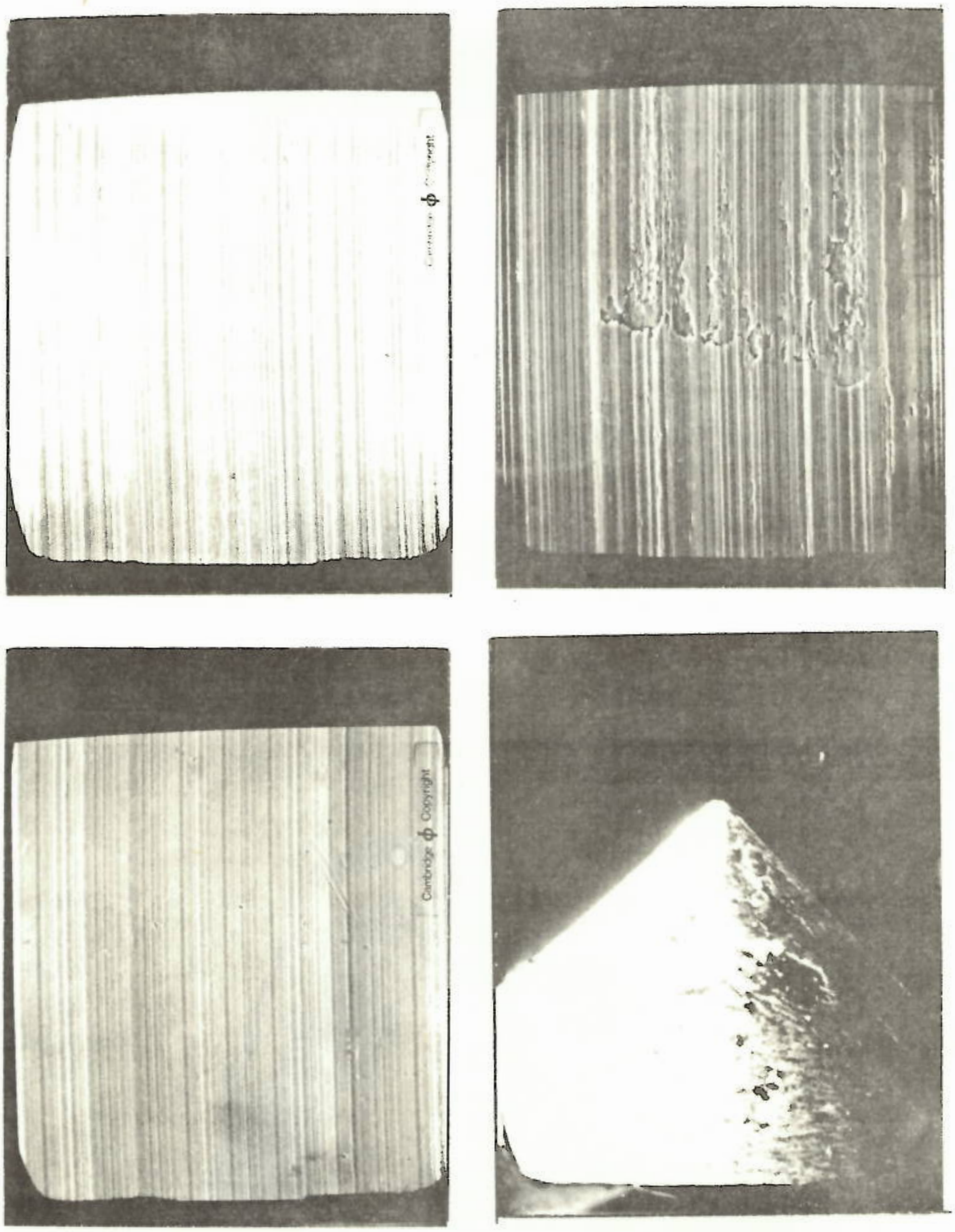
PLATE 8



UNIVERSAL VICE SHOWING BALL AND SPRING ARRANGEMENT FOR CONSISTENT RETURN TO ZERO

PLATE 12

x 431 0·001 i.p.r. x 500 0·004 i.p.r.



x 431 MANGANESE BRONZE DIAMOND STYLUS x 940

PLATE 9

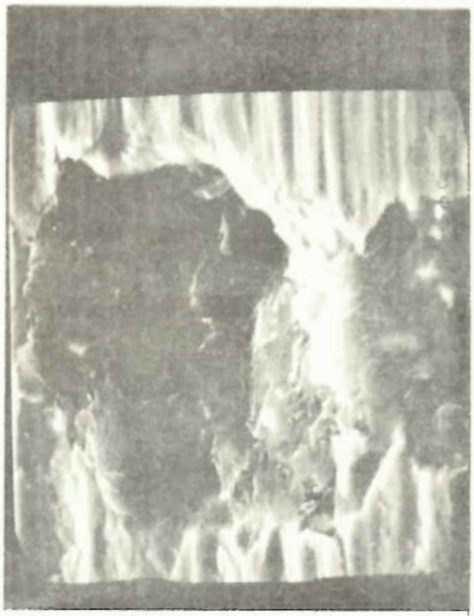
STEREOSCAN PHOTOGRAPHS SHOWING SURFACES AT DIFFERENT FEEDS AND DIAMOND STYLUS

B.S. 1452

x 94

x 1875

(a)



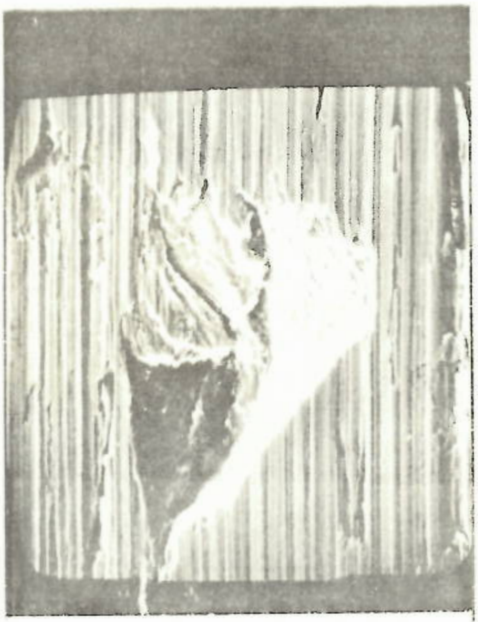
(b)

B.S. 2789

x 94

x 950

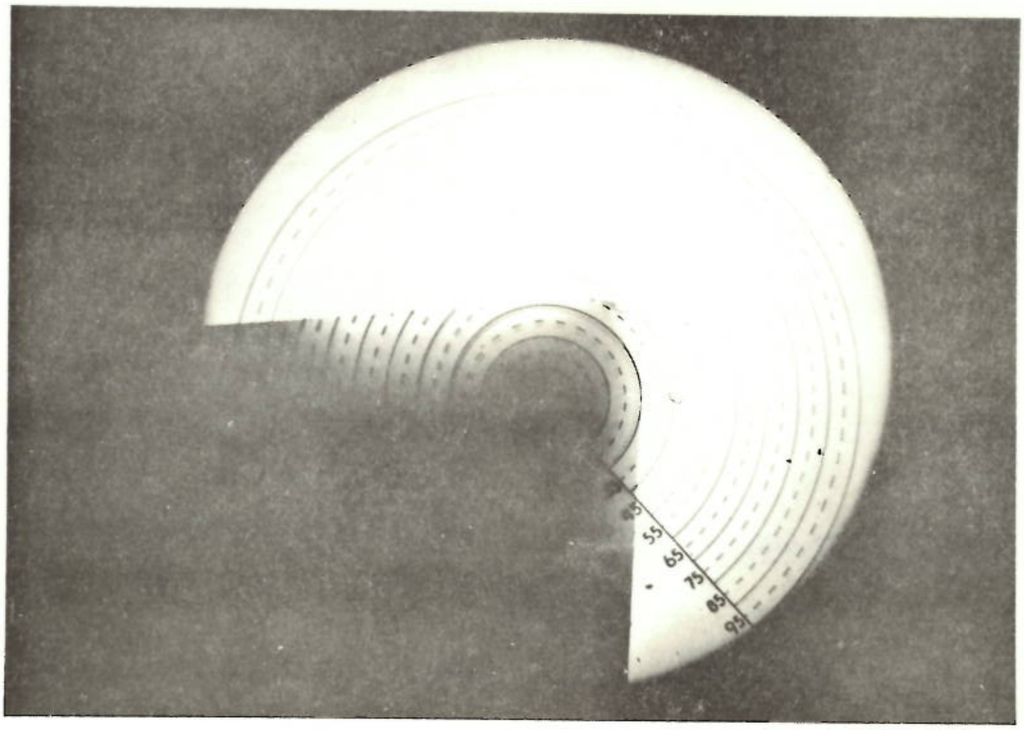
(c)



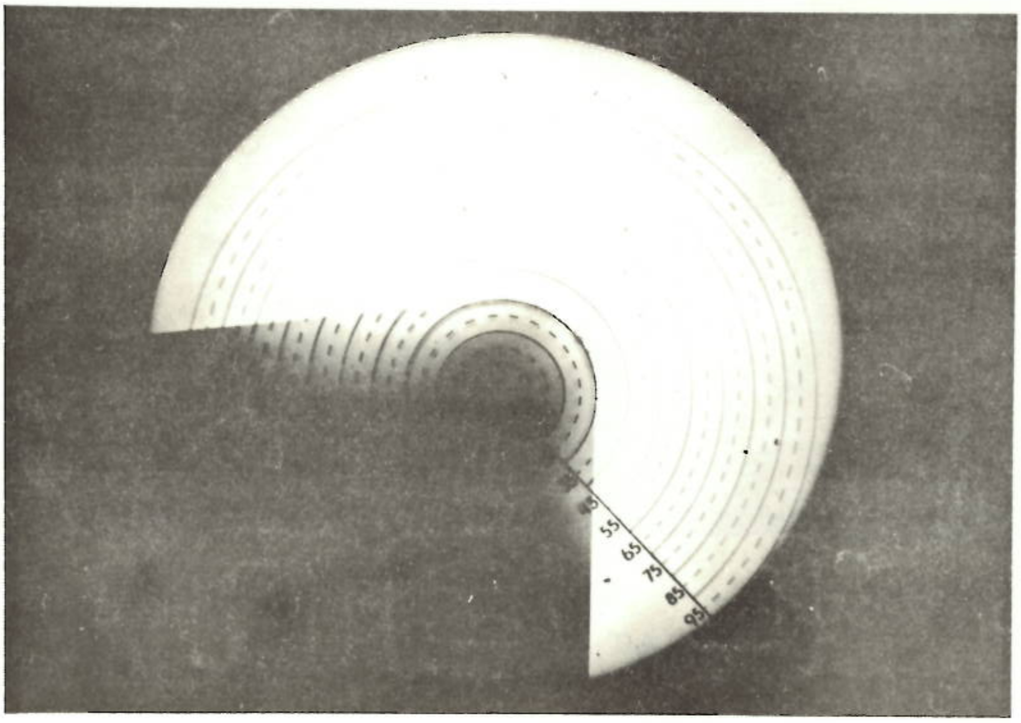
(d)

STEREOSCAN PHOTOGRAPHS SHOWING HOLES IN CAST IRON BARS

PLATE 10



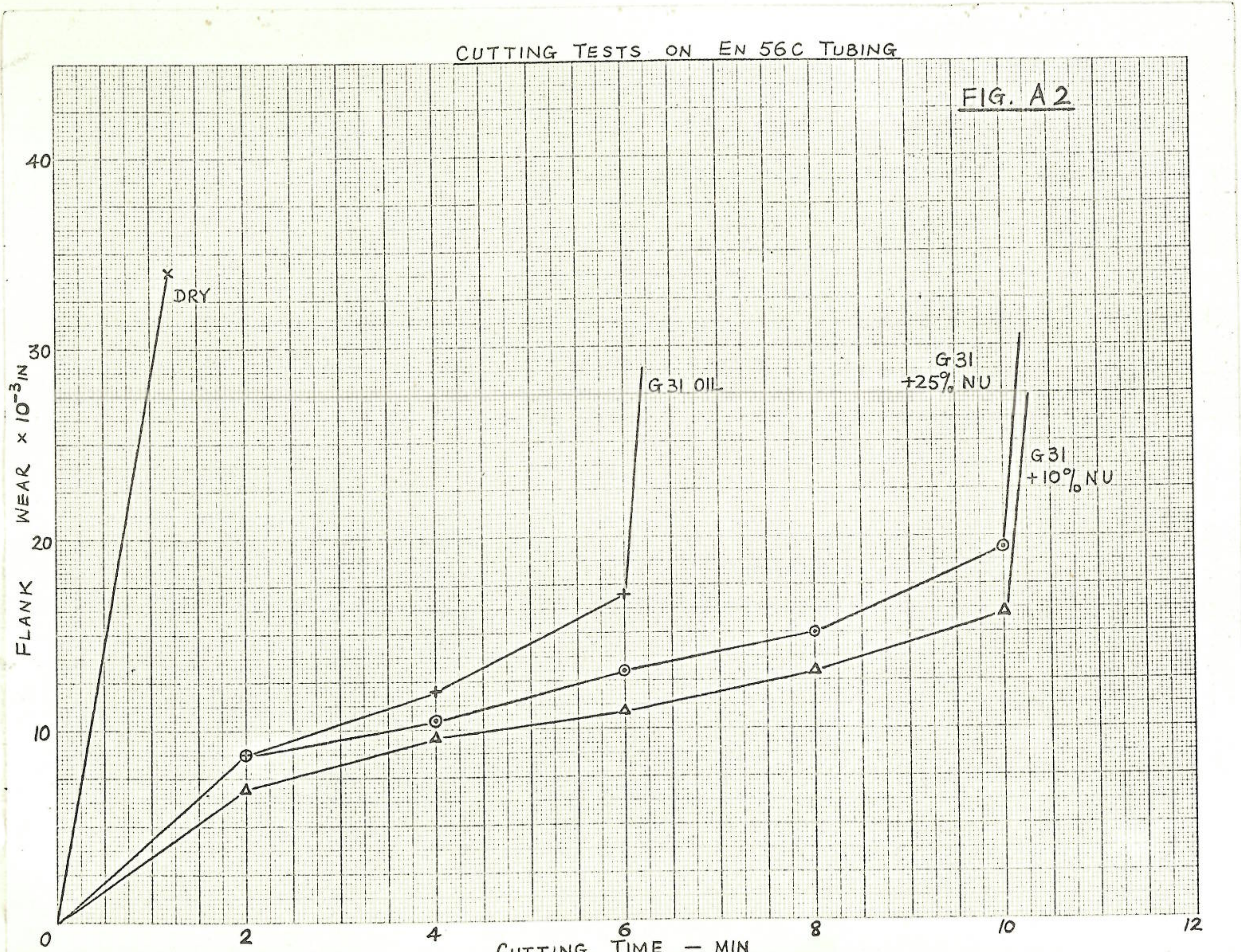
(a)



(b)

SETTING FOR NOSE RADIUS BLENDING

PLATE II


CUTTING TESTS ON EN 56C TUBING
FIG. A2
DRY
G31 OIL
G31
+25% NU
G31
+10% NU
FLANK WEAR × 10^{-3} IN
CUTTING TIME — MIN
0
2
4
6
8
10
12
10
20
30
40

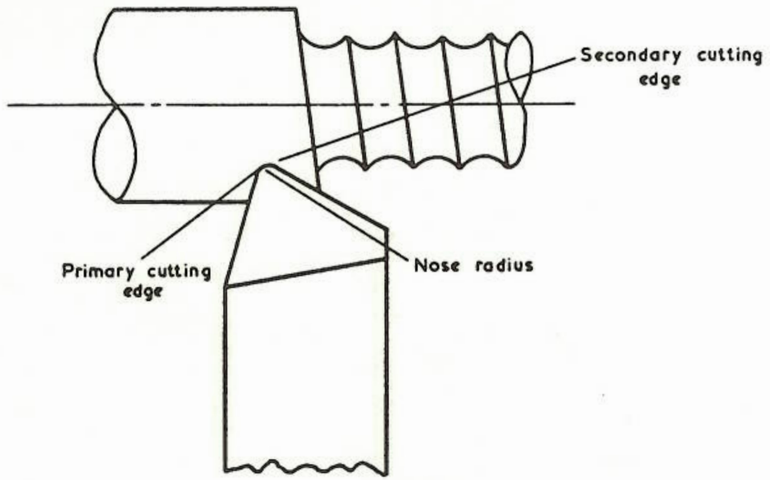


FIG.1. CUTTING OPERATION SHOWING PRIMARY AND SECONDARY CUTTING EDGES AND WAVE FORM LEFT ON THE FINISHED SURFACE.

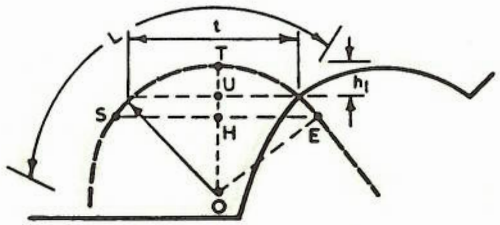


FIG.2. PLAN VIEW OF CUTTING TOOL SHOWING PEAK-TO-VALLEY HEIGHT AND ACTIVE LENGTH OF CUTTING EDGE.

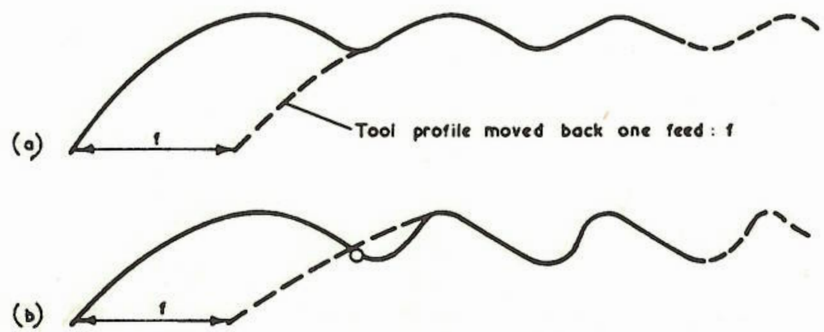


FIG.3. PROFILE GENERATED BY TOOL POINT (a) IN ABSENCE OF SIDE FLOW AND (b) WITH SIDE FLOW.

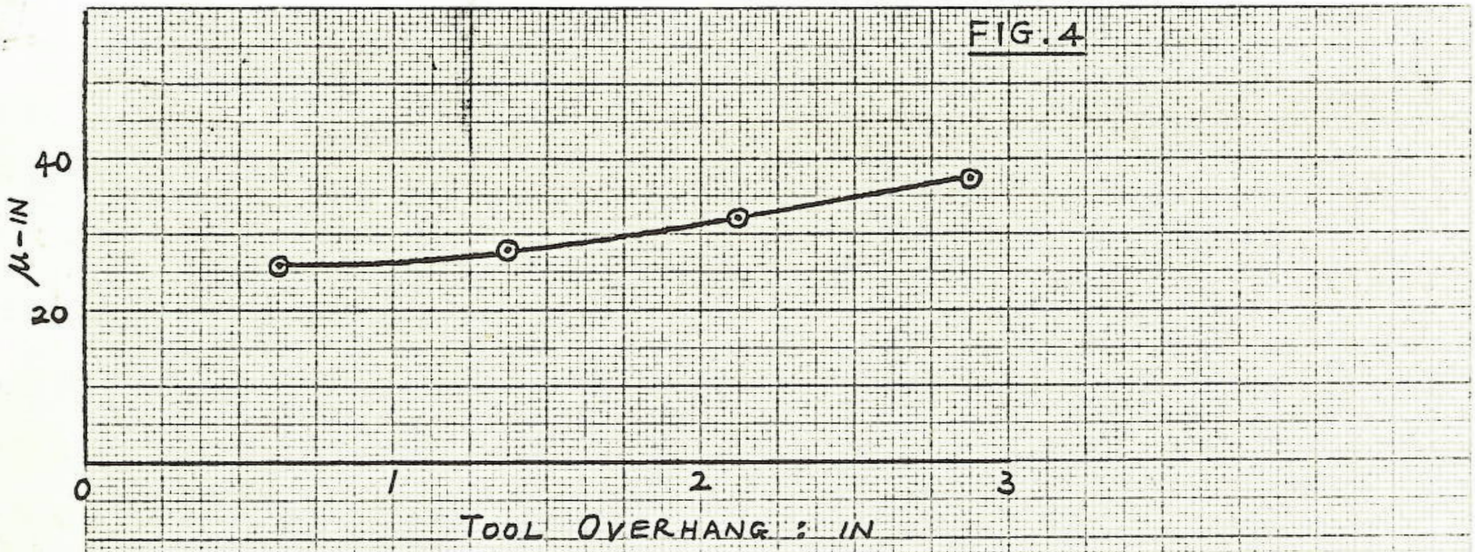


FIG. 4

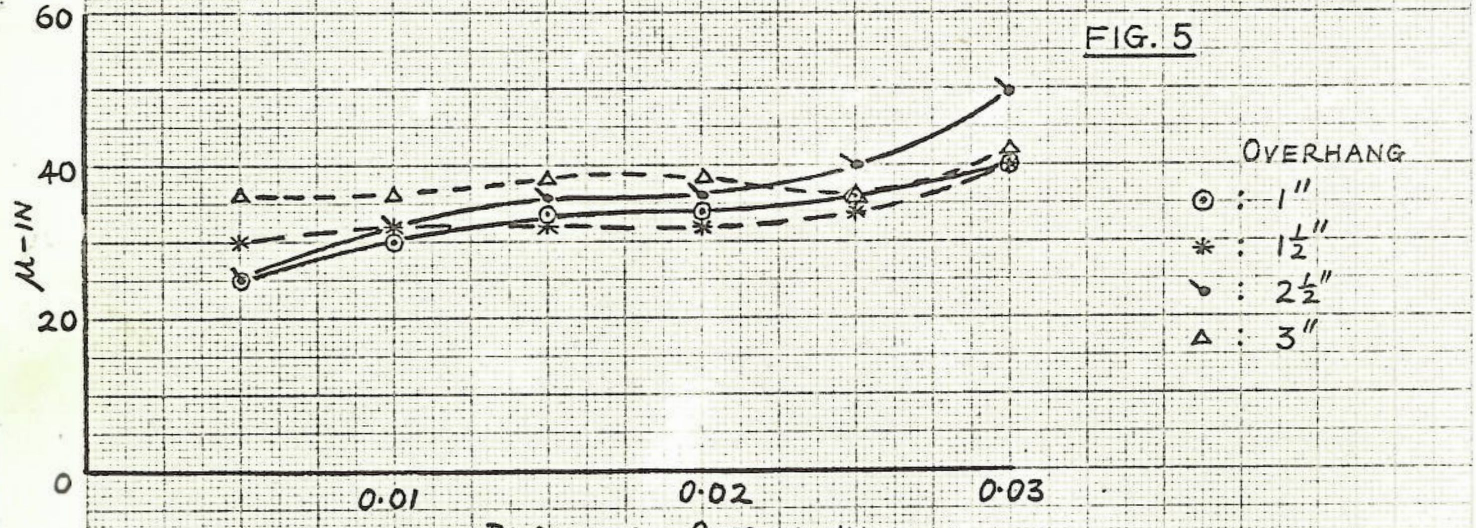


FIG. 5

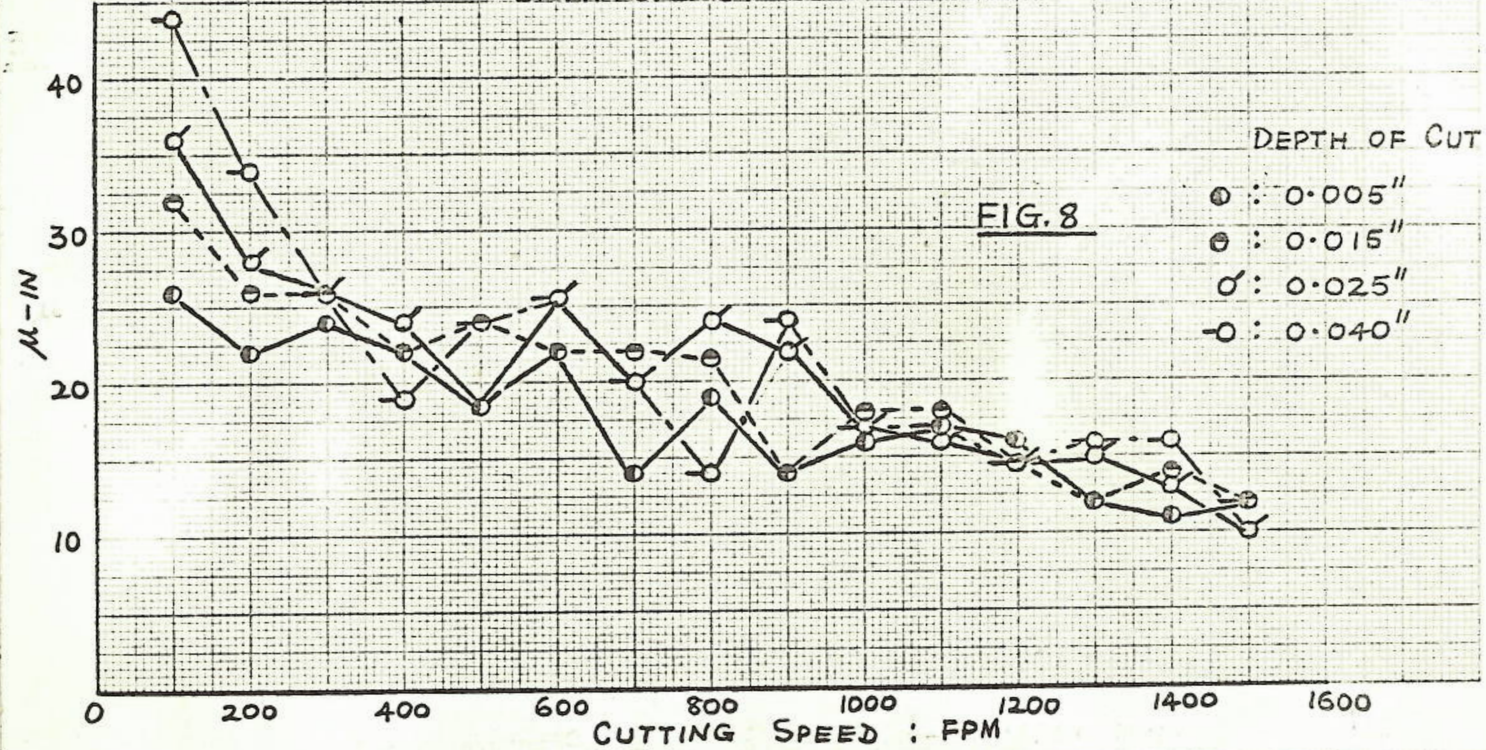


FIG. 8

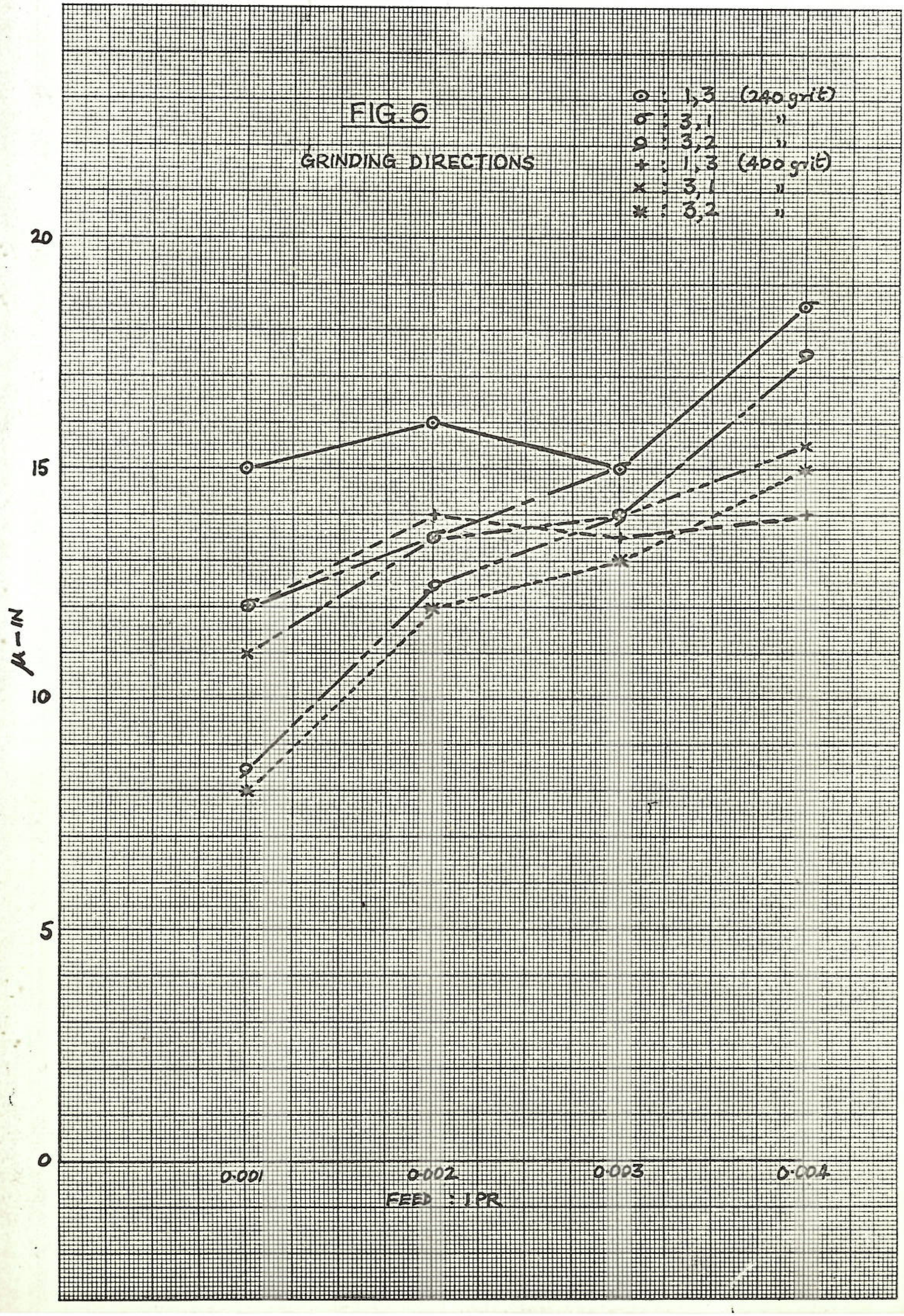


FIG. 6
GRINDING DIRECTIONS
1,3 (240 grit)
3,1 "
3,2 "
1,3 (400 grit)
3,1 "
3,2 "
20
15
10
5
0
μ-IN
0·001
0·002
0·003
0·004
FEED : IPR

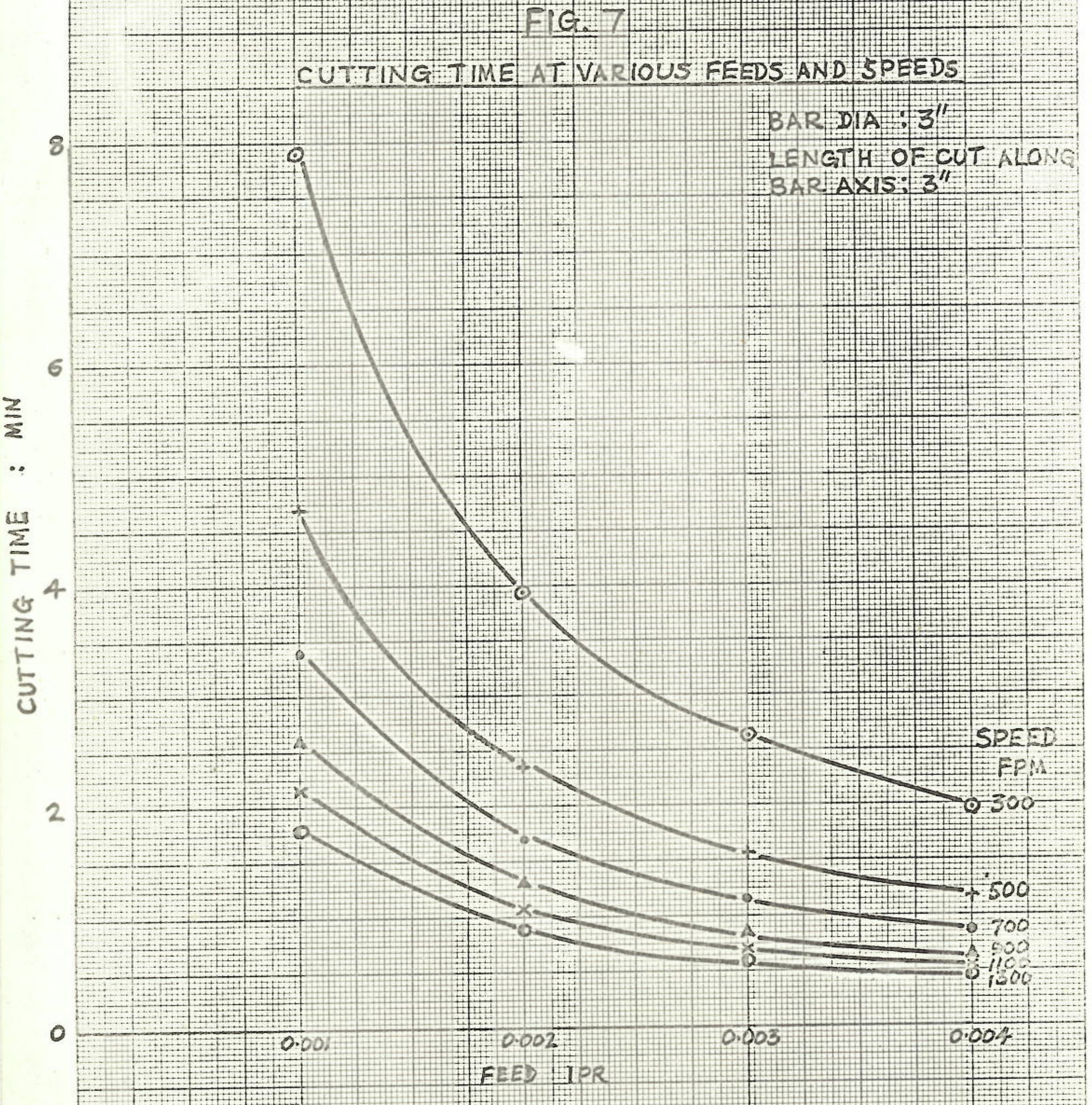


FIG. 7
CUTTING TIME AT VARIOUS FEEDS AND SPEEDS
BAR DIA : 3"
LENGTH OF CUT ALONG BAR AXIS: 3"
CUTTING TIME : MIN
8
6
4
2
0
SPEED FPM
300
500
700
900
1100
1300
0·001
0·002
0·003
0·004
FEED IPR

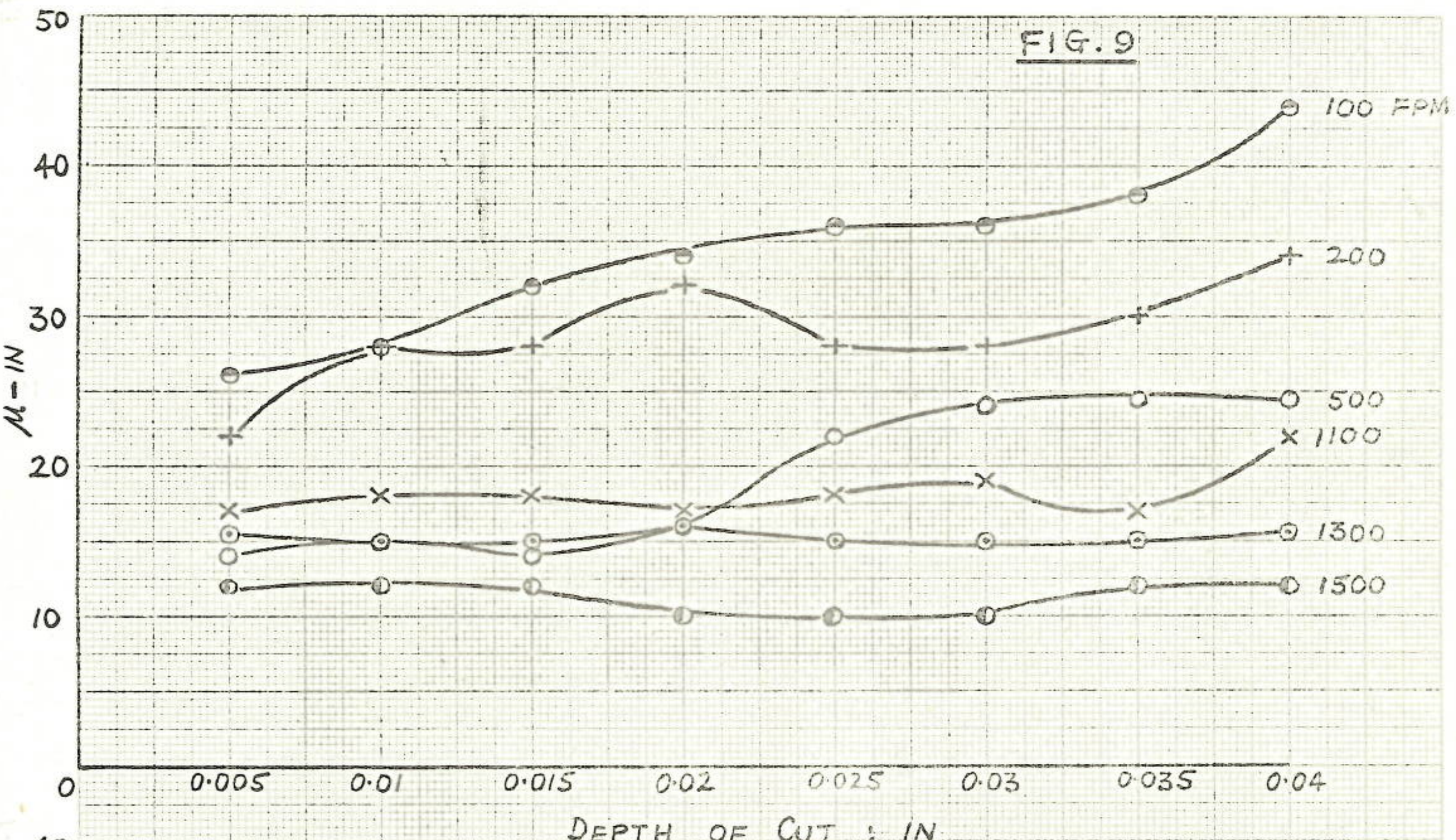


FIG. 9
100 FPM
200
500
1100
1300
1500
μ - IN
DEPTH OF CUT : IN

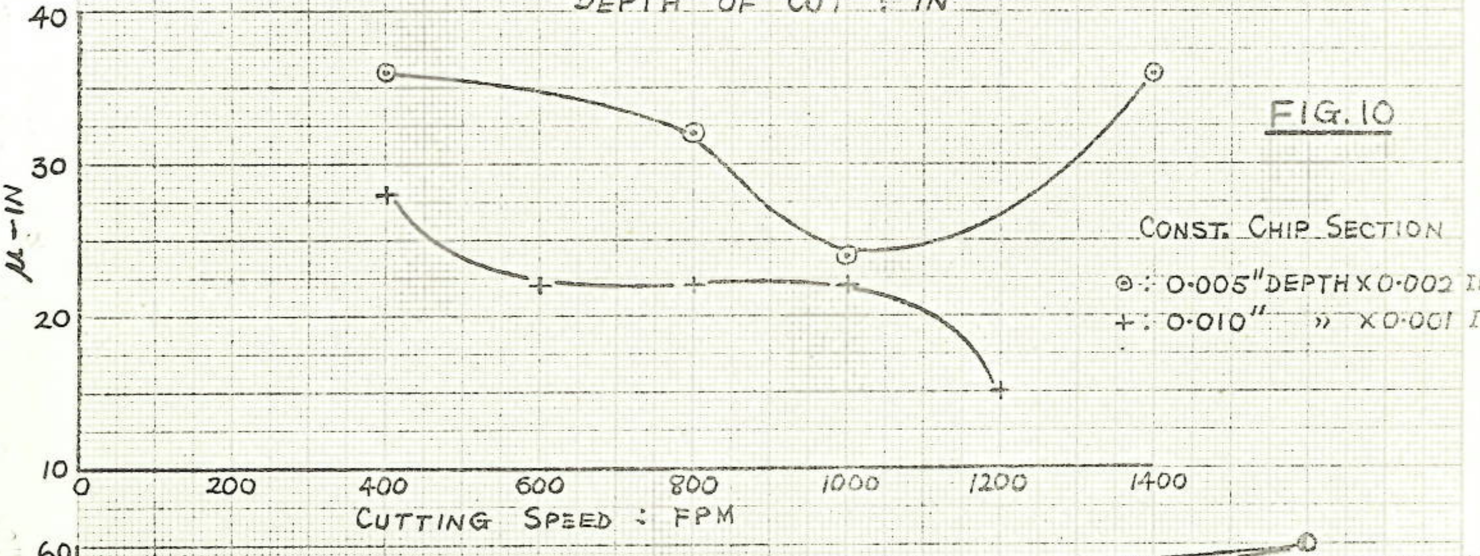


FIG. 10
CONST. CHIP SECTION
⊙ : 0·005" DEPTH X 0·002 IP
+ : 0·010" » X 0·001 IP
μ - IN
CUTTING SPEED : FPM

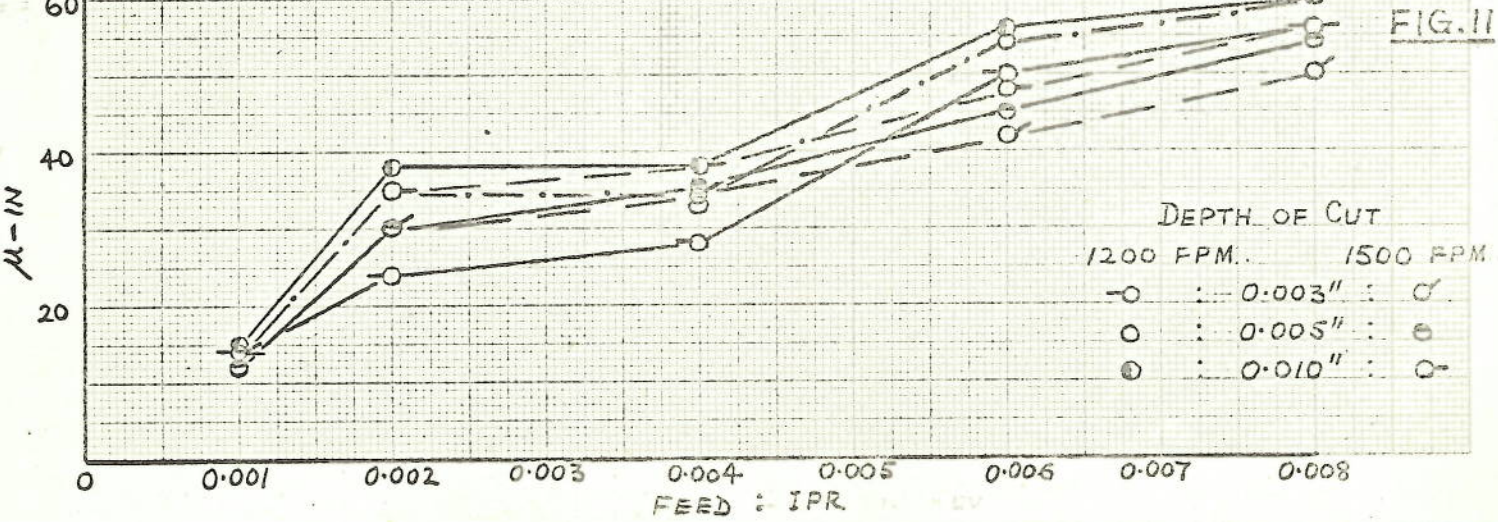


FIG. 11
DEPTH OF CUT
1200 FPM
1500 FPM
0·003"
0·005"
0·010"
μ - IN
FEED : IPR

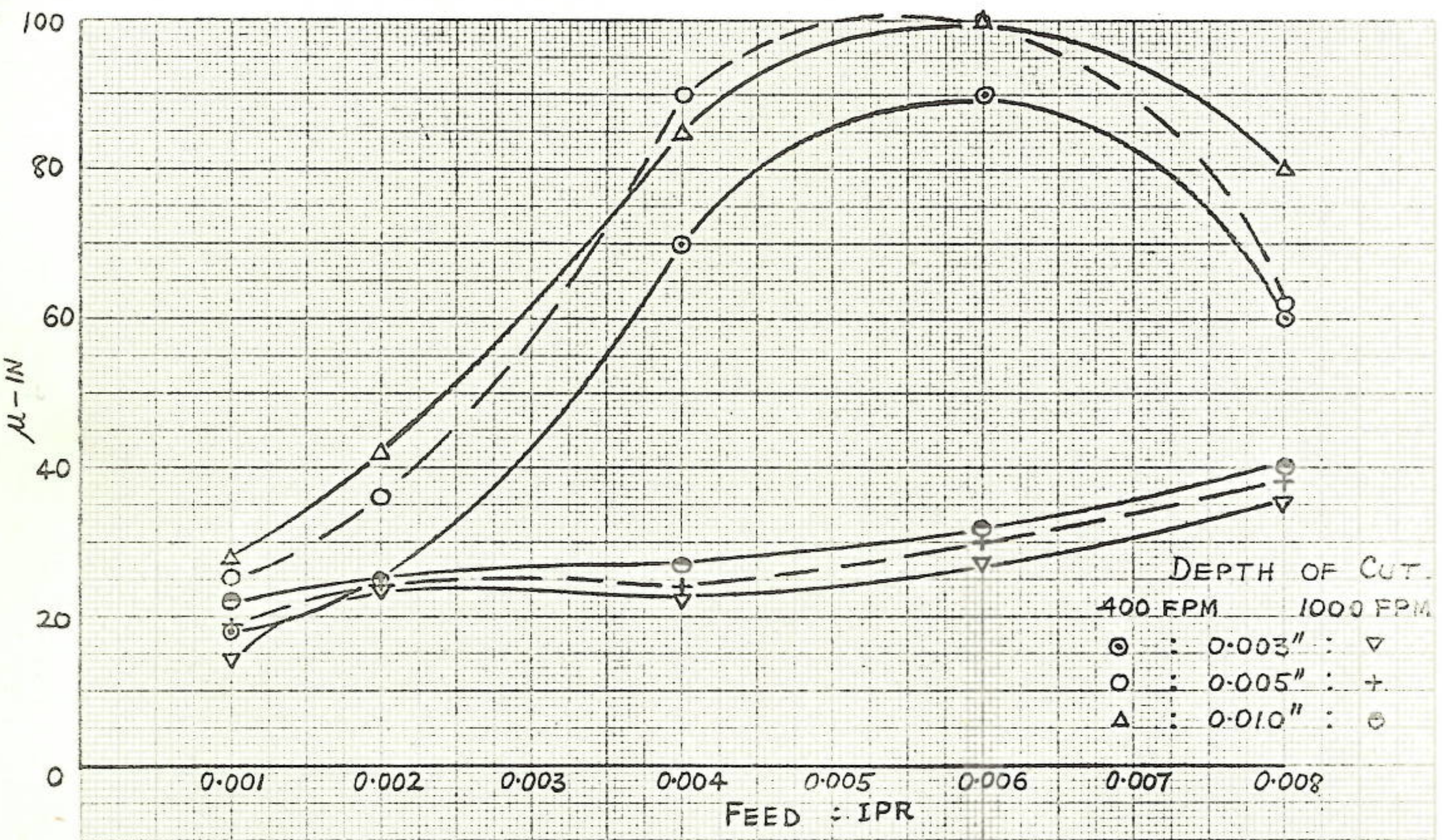

100
80
60
40
20
0
μ-IN
0·001
0·002
0·003
0·004
0·005
0·006
0·007
0·008
FEED : IPR
DEPTH OF CUT.
400 FPM
1000 FPM
0·003" :
0·005" :
0·010" :

FIG. 12

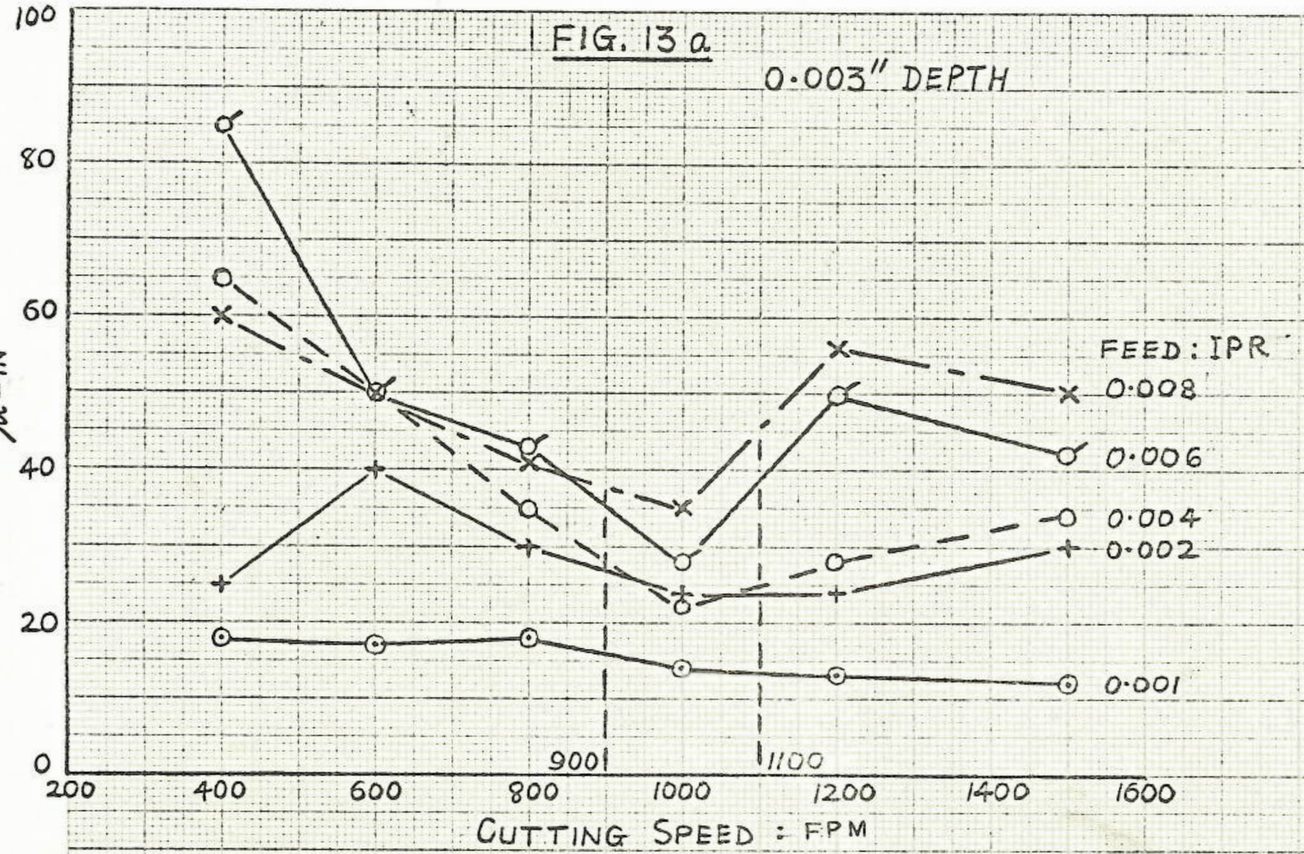


FIG. 13 a
0·003" DEPTH
FEED : IPR
0·008
0·006
0·004
0·002
0·001
µ-IN
CUTTING SPEED : FPM
900
1100

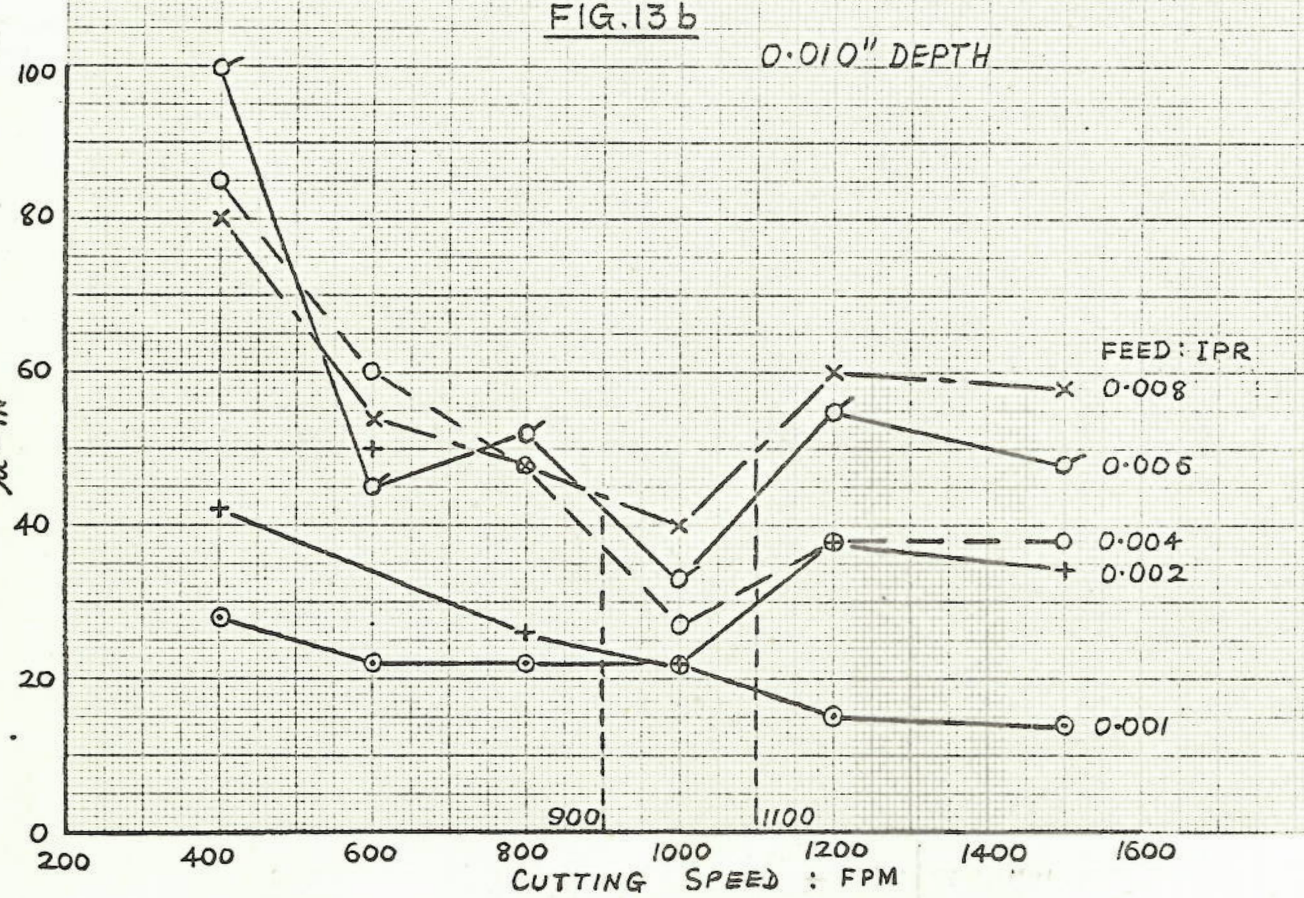


FIG. 13 b
0·010" DEPTH
FEED : IPR
0·008
0·006
0·004
0·002
0·001
µ-IN
CUTTING SPEED : FPM
900
1100

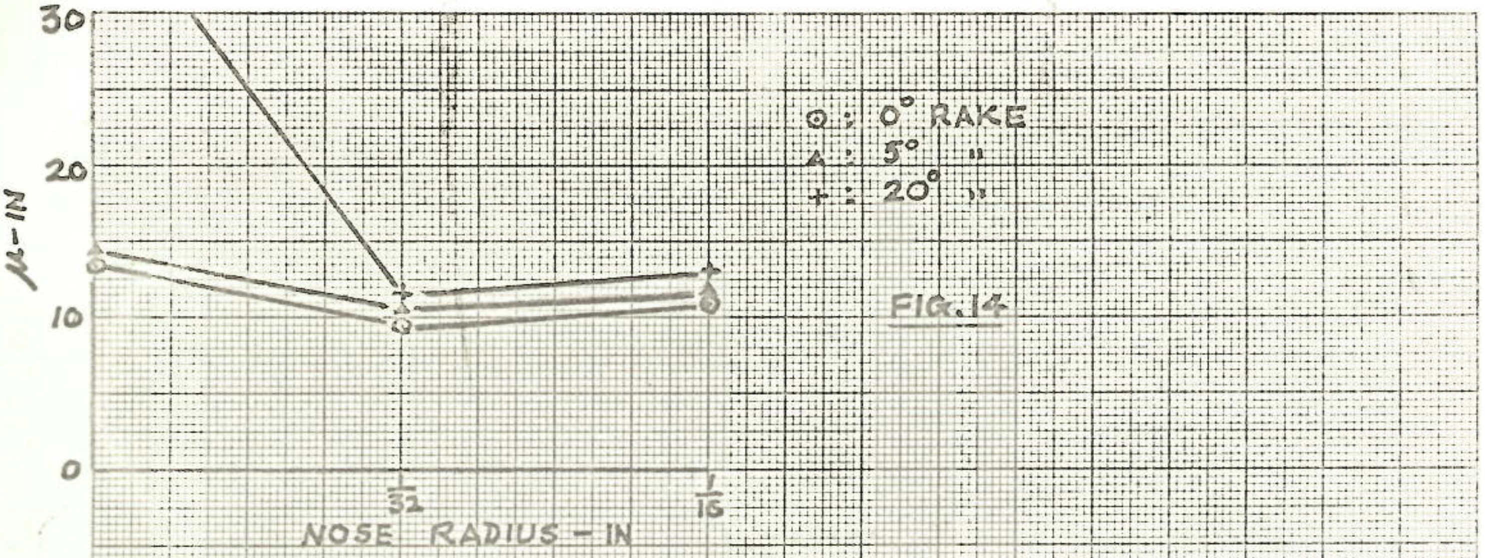


FIG. 14

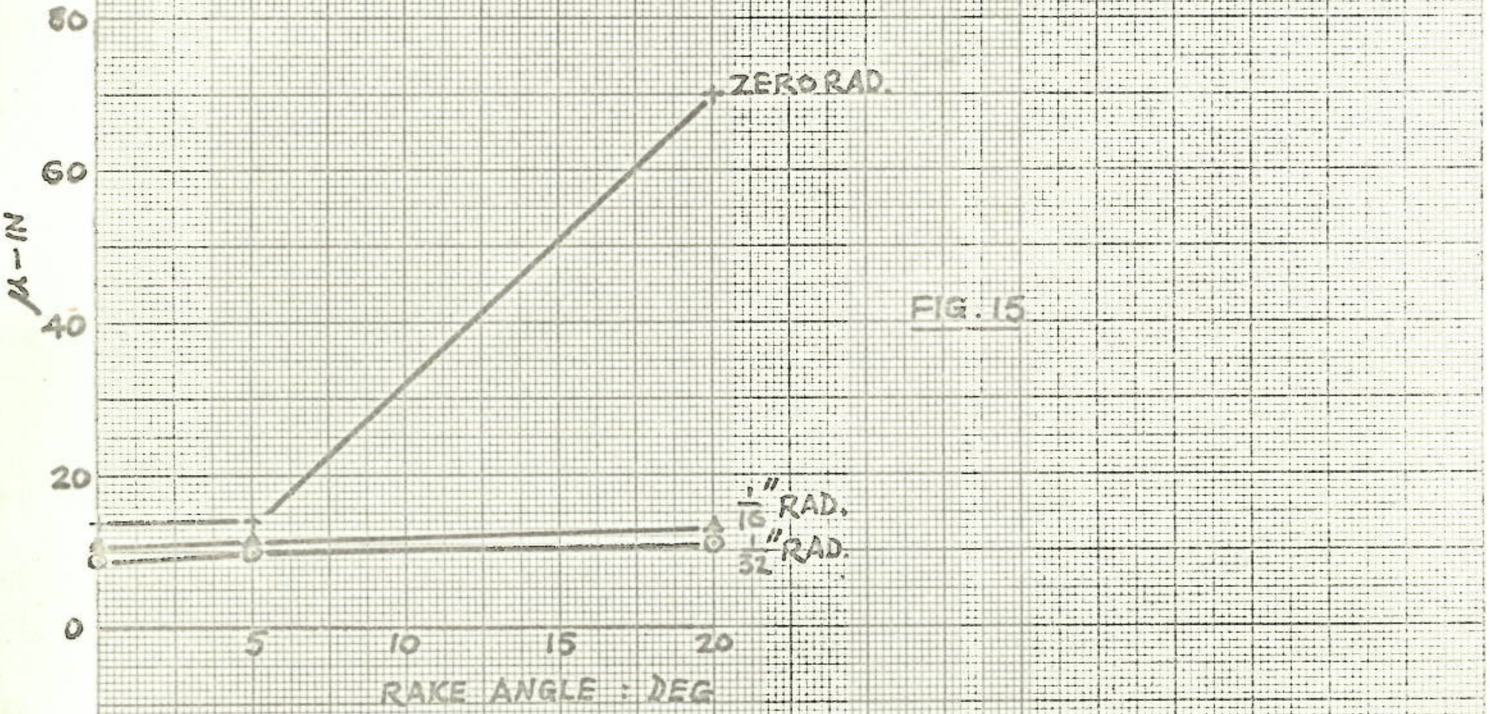


FIG. 15

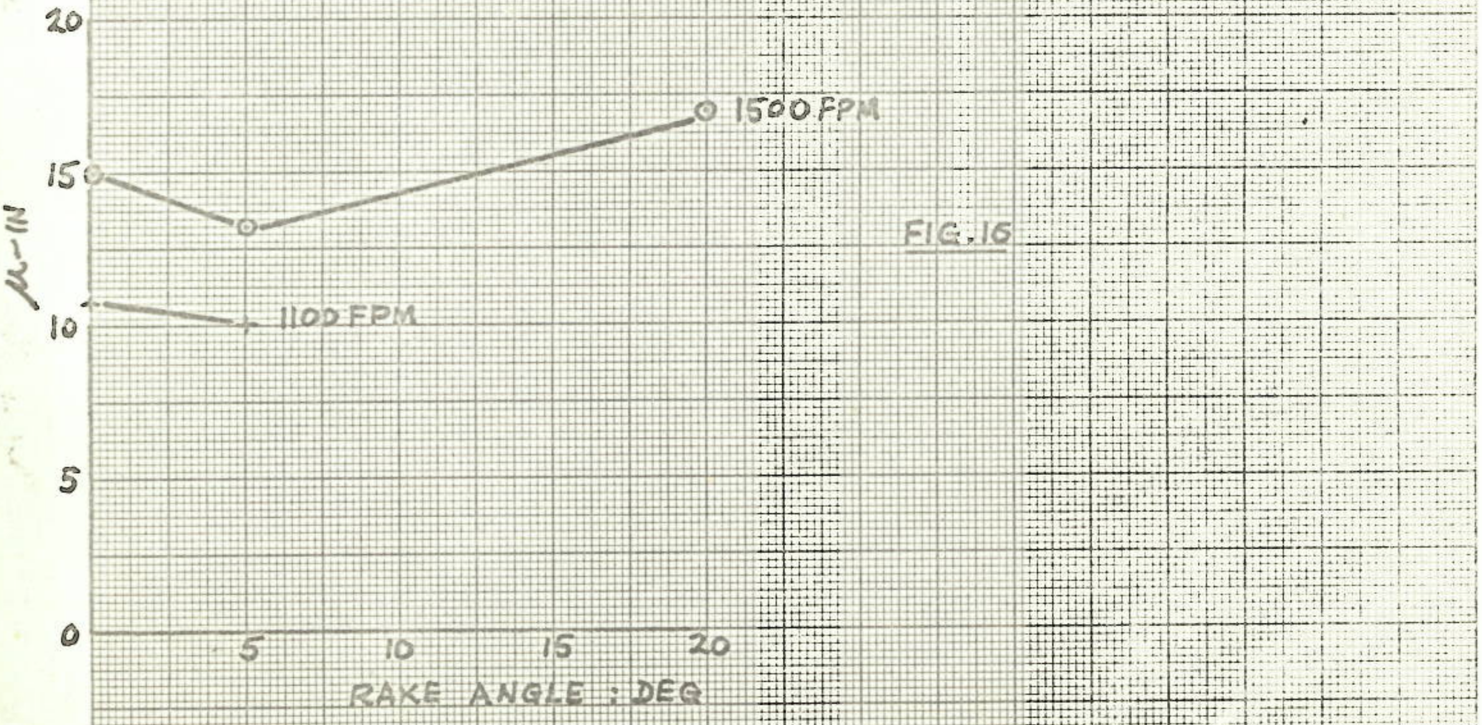
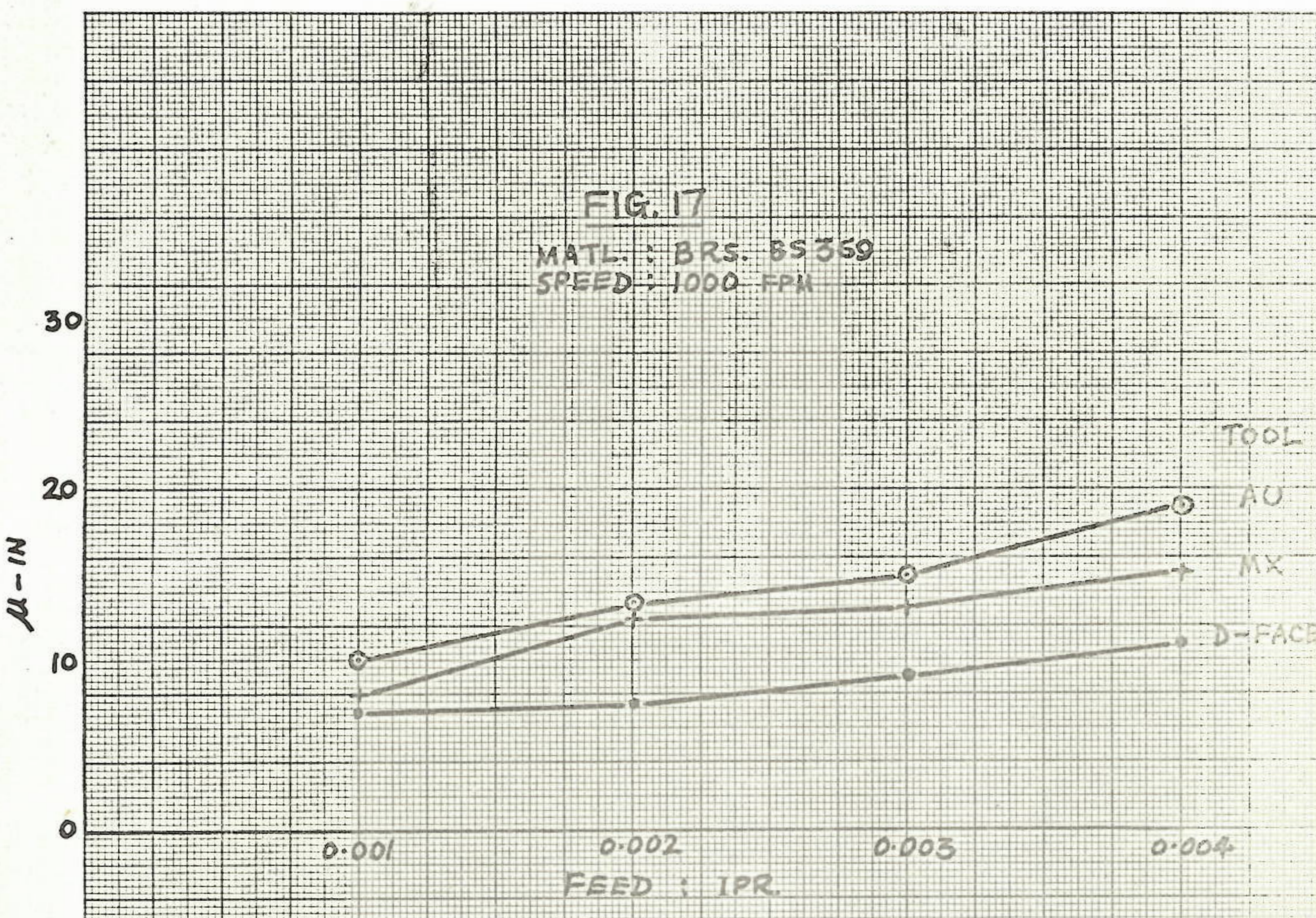
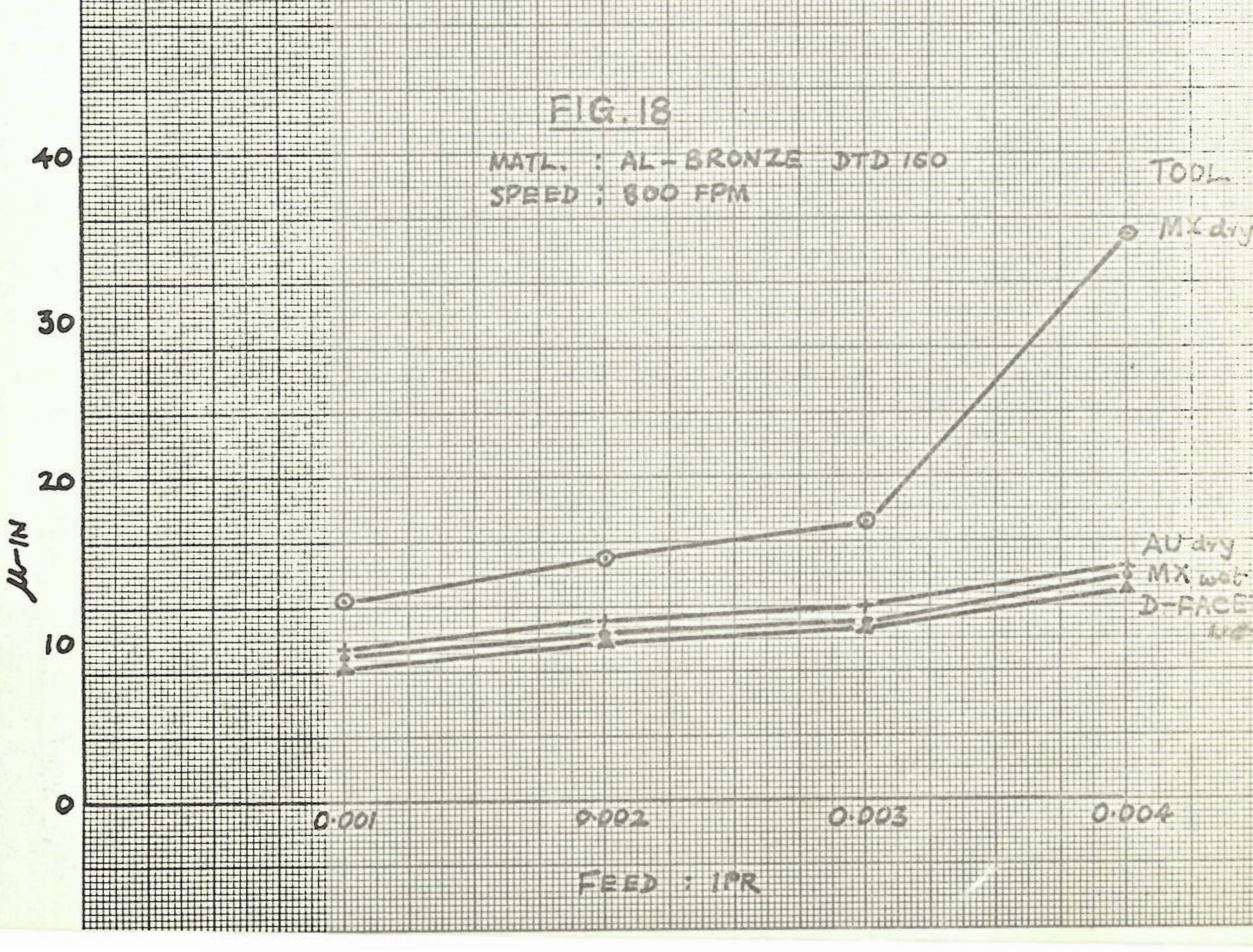


FIG. 16



MATL. : BRS. BS 369
SPEED : 1000 FPM
30
20
10
0
μ-IN
TOOL
AU
MX
D-FACE
0·001
0·002
0·003
0·004
FEED : IPR

FIG. 17



MATL. : AL-BRONZE DTD 160
SPEED : 800 FPM
40
30
20
10
0
μ-IN
TOOL
MX dry
AU dry
MX wet
D-FACE
0·001
0·002
0·003
0·004
FEED : IPR

FIG. 18

FIG. 19

MATL : C.I. BS 2789
SPEED : 700 FPM

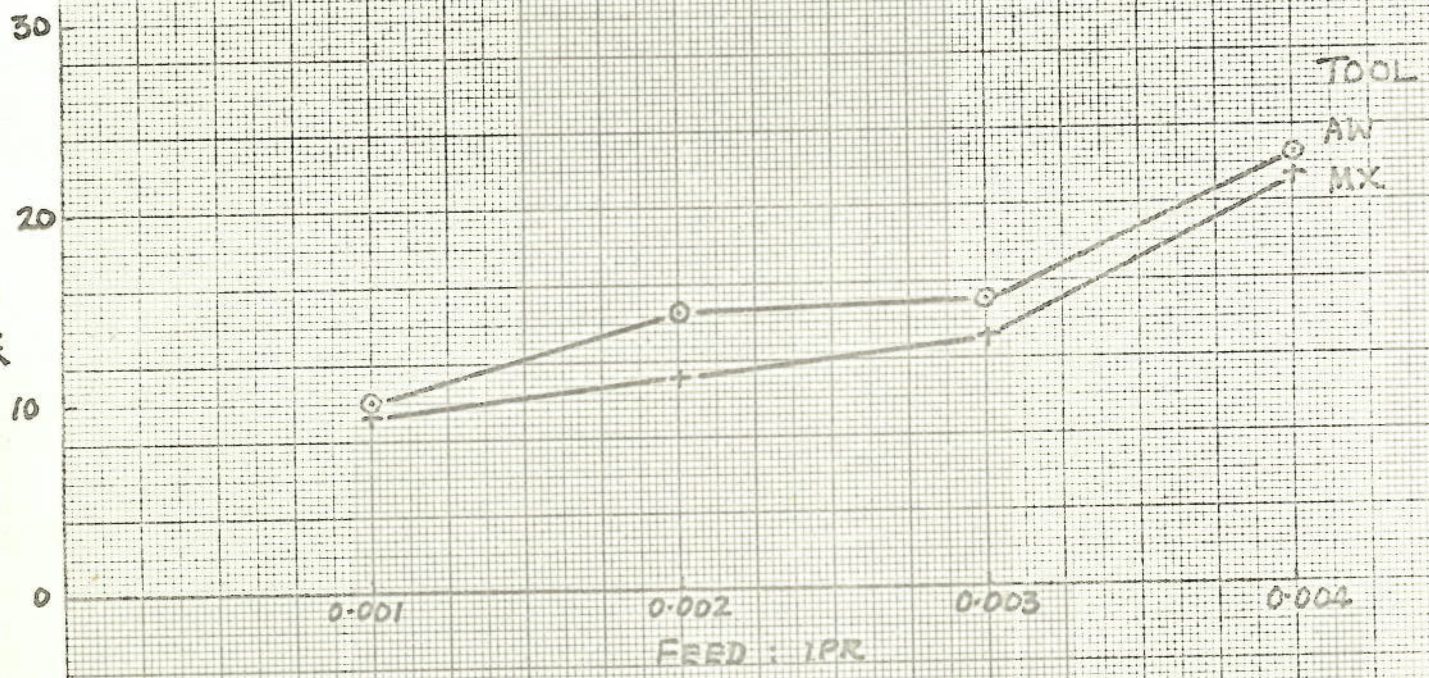
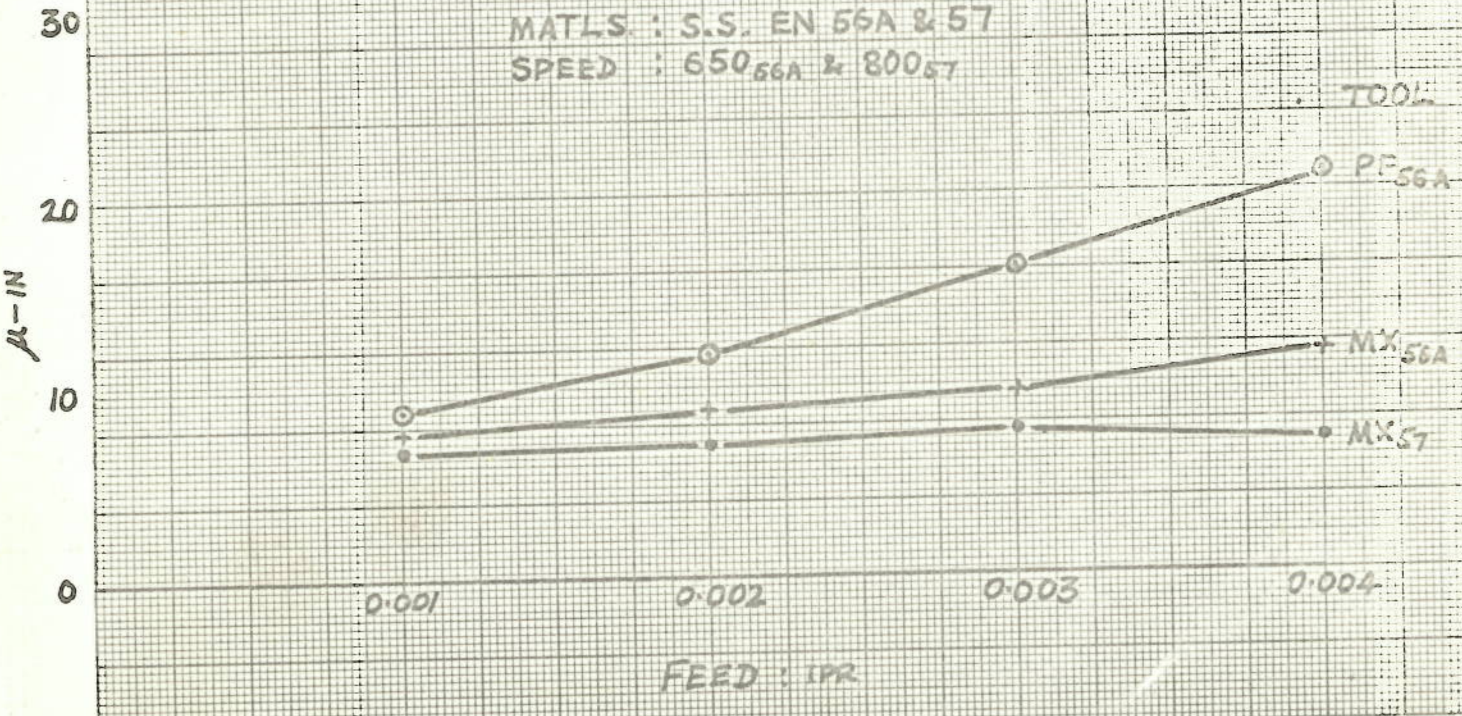


FIG. 20

MATLS : S.S. EN 56A & 57
SPEED : 650_{56A} & 800_{57}



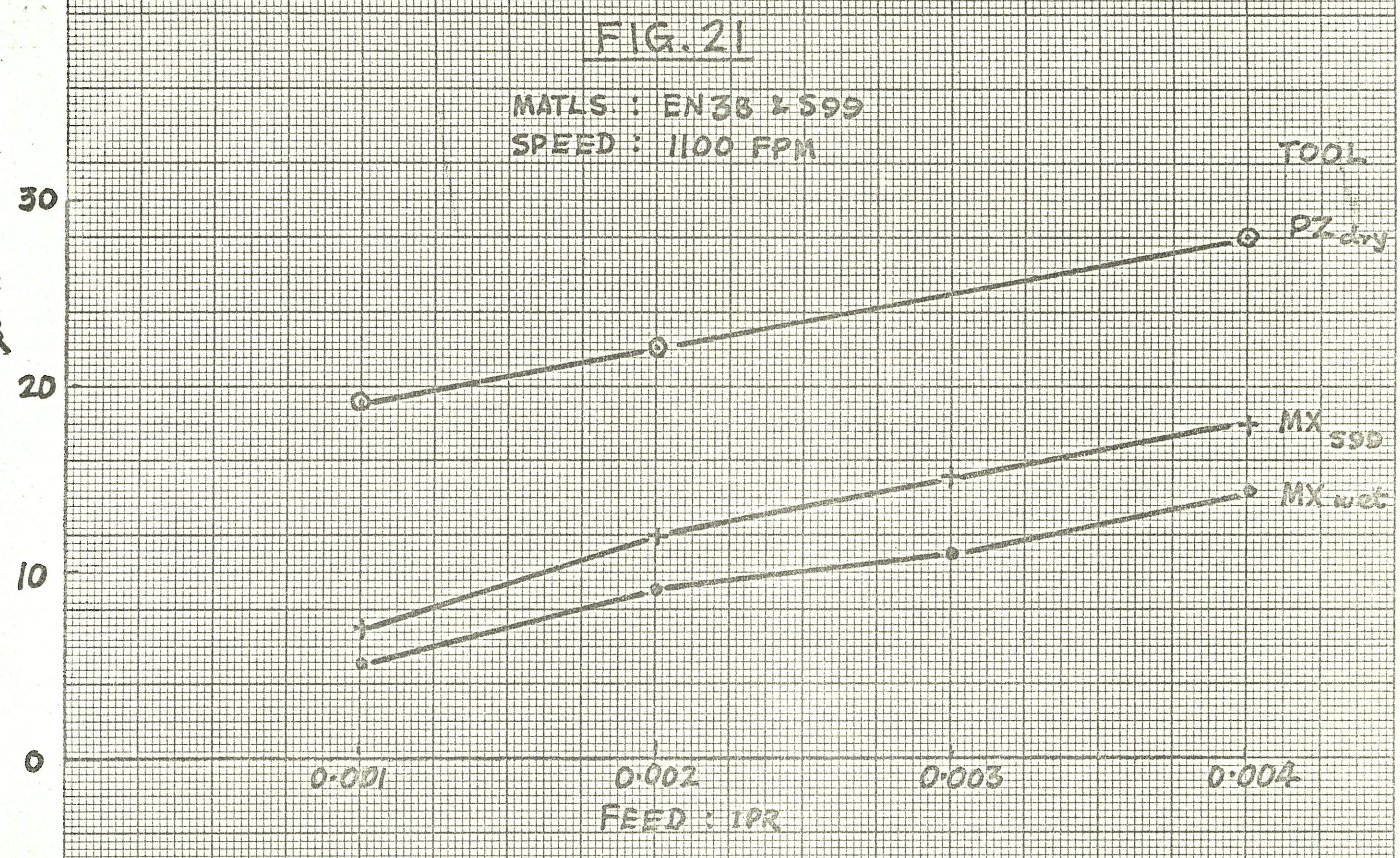


FIG. 21
MATLS : EN 38 & S99
SPEED : 1100 FPM
TOOL
PZ dry
MX S99
MX wet
μ-IN
30
20
10
0
0·001
0·002
0·003
0·004
FEED : IPR